VOLUME 105 PART A NUMBER 20 APRIL 1958

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

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PART A

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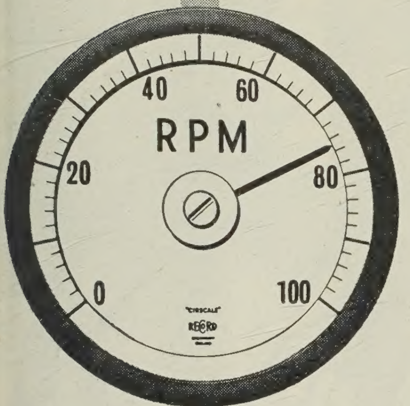

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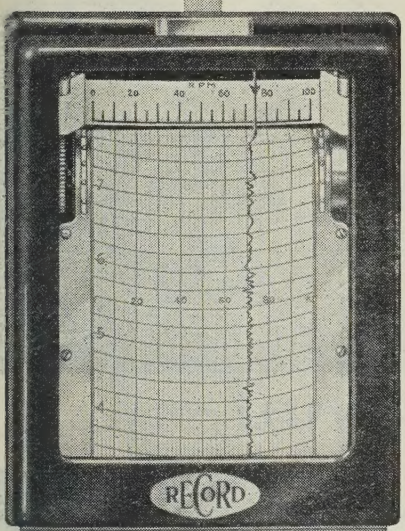

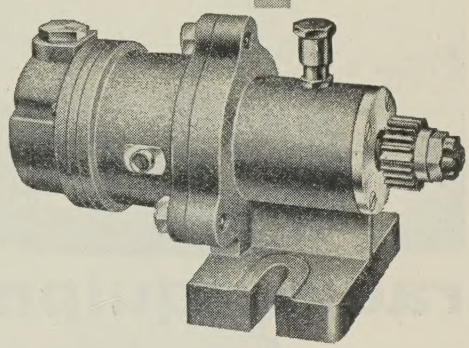

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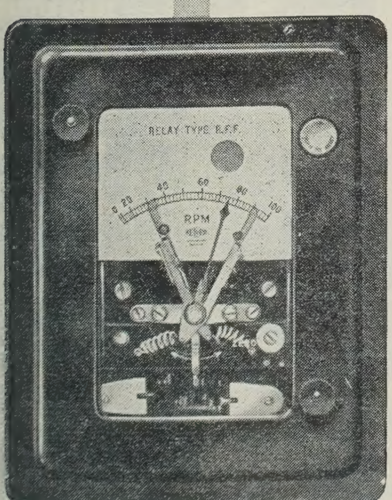

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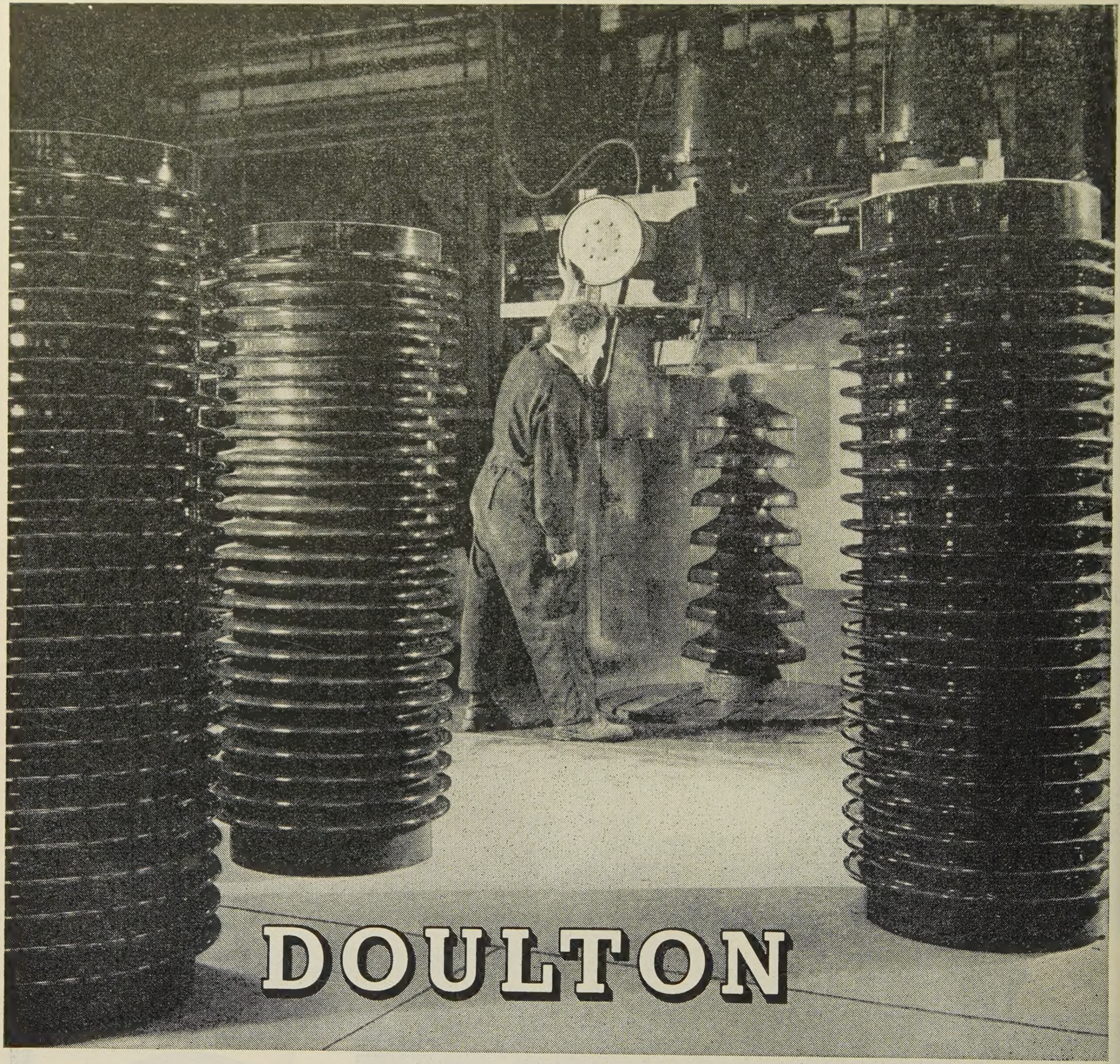

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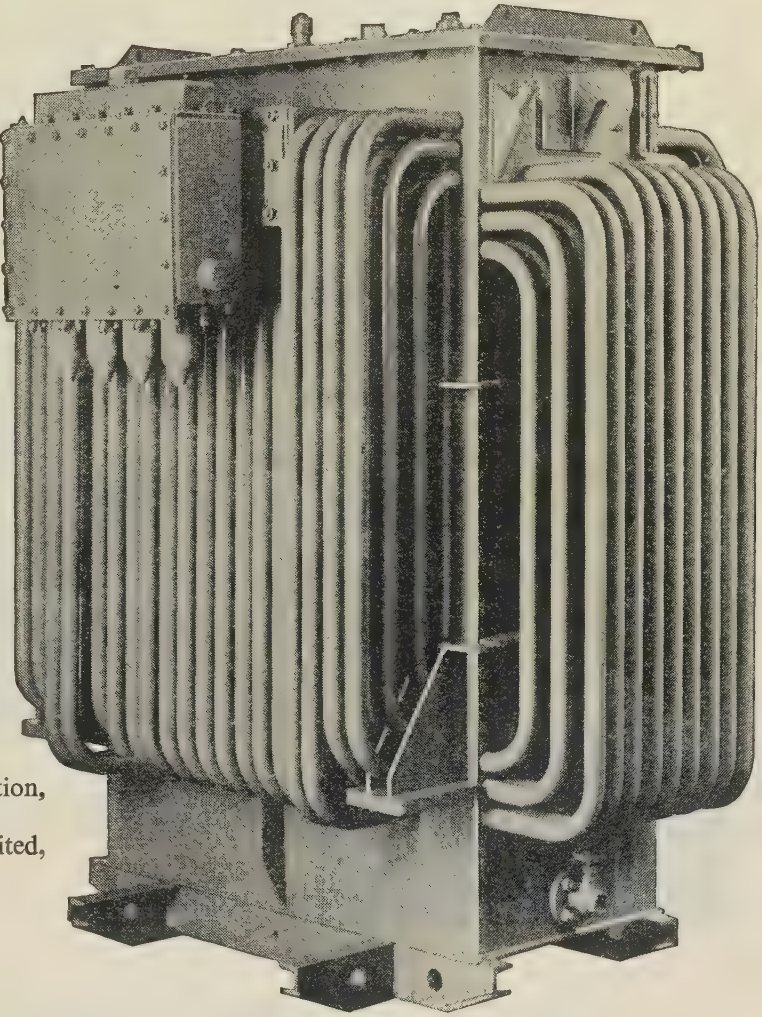

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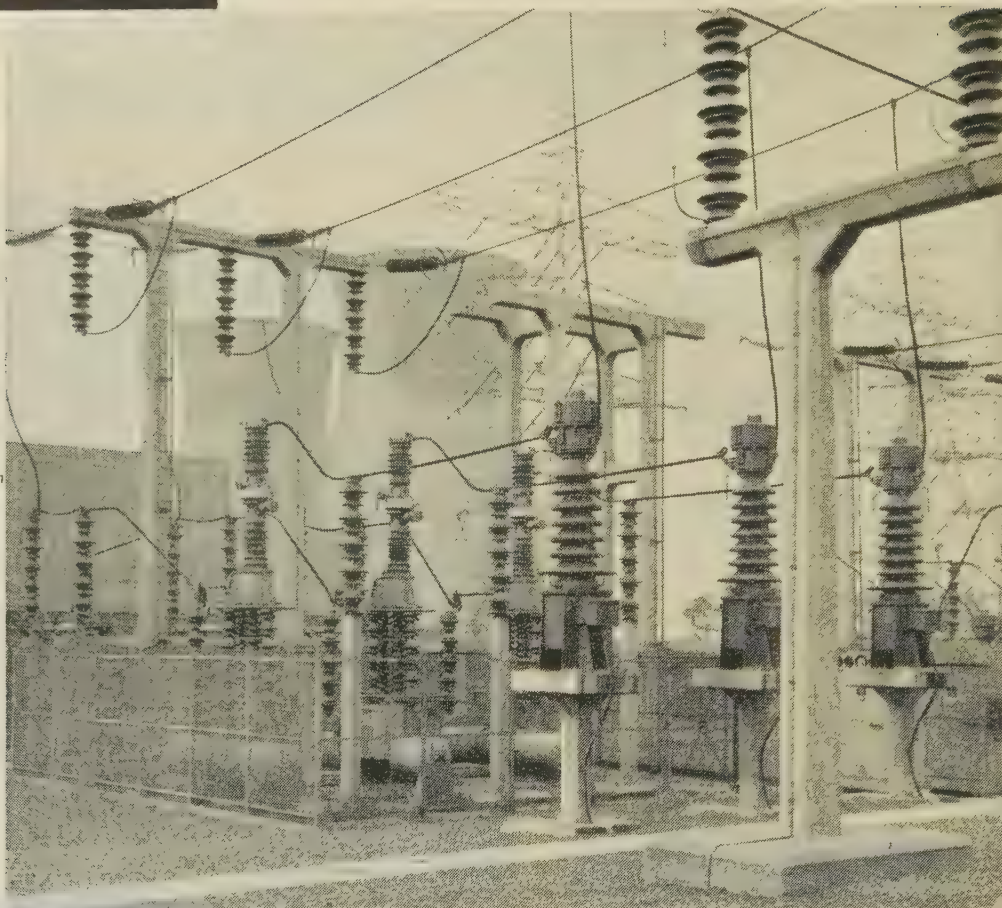

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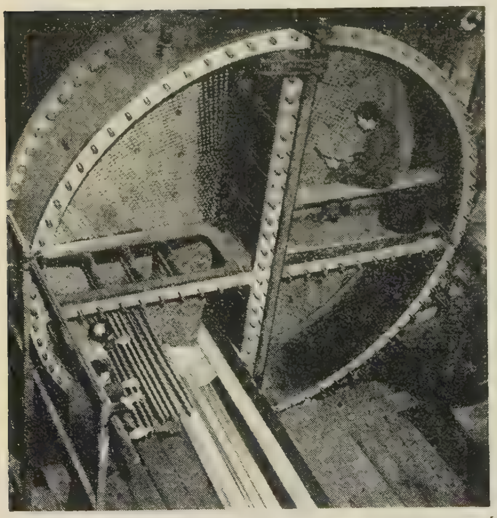

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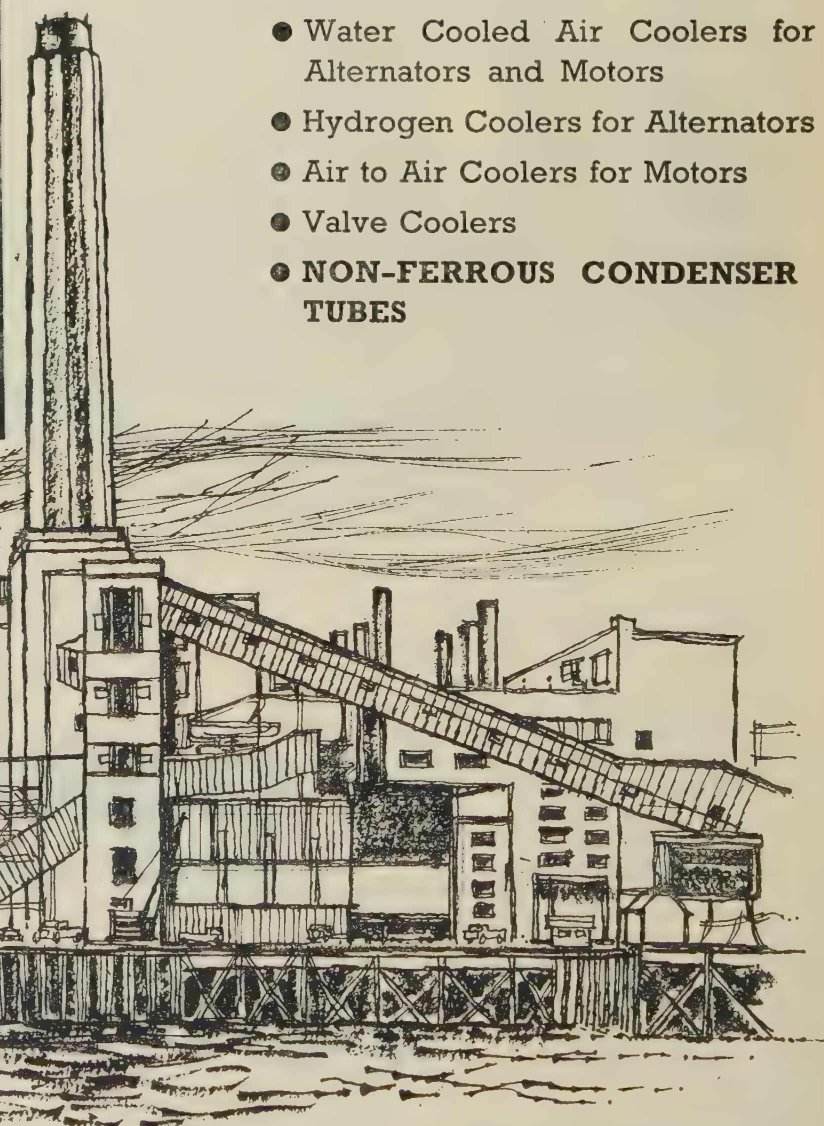

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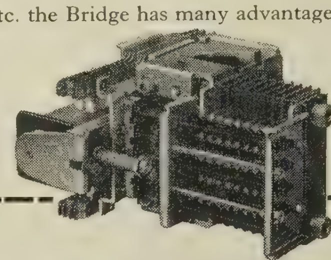

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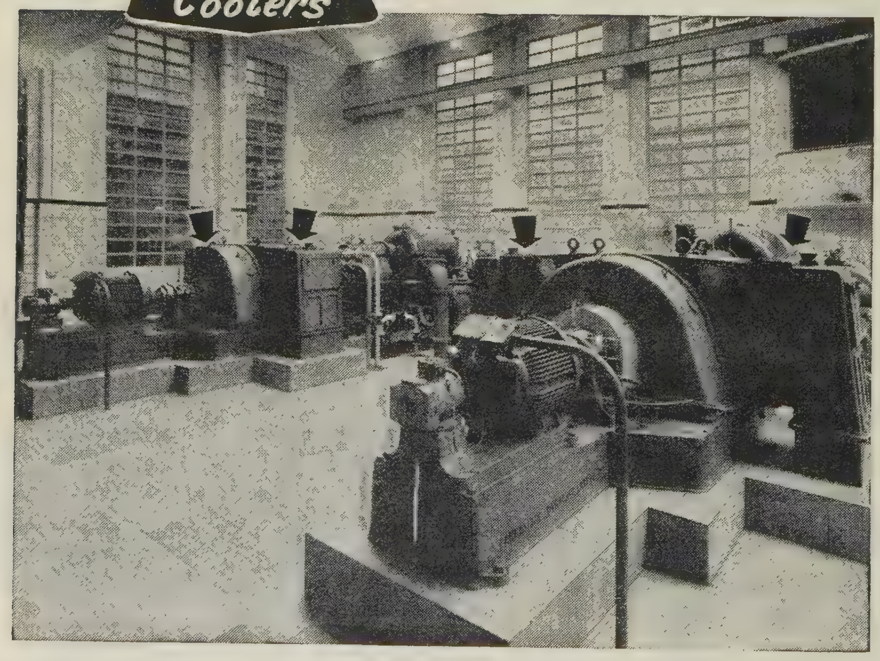

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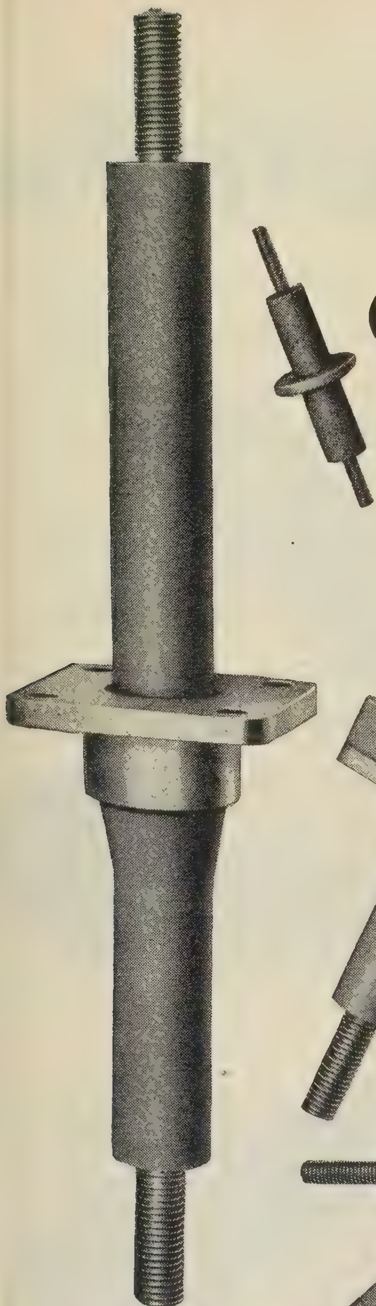


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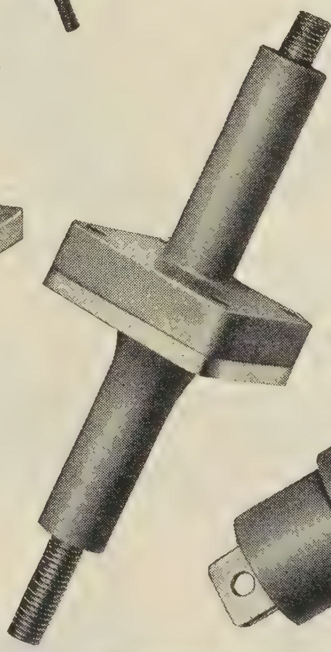
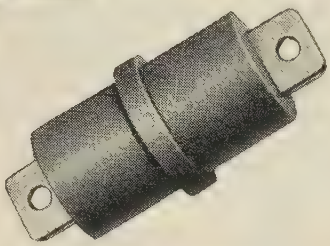

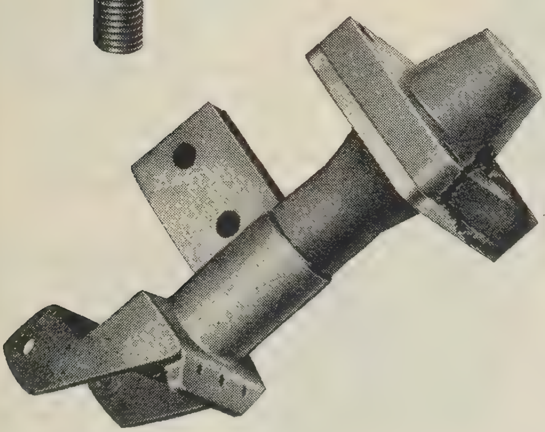

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THE PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

TEN-YEAR INDEX

1942—1951

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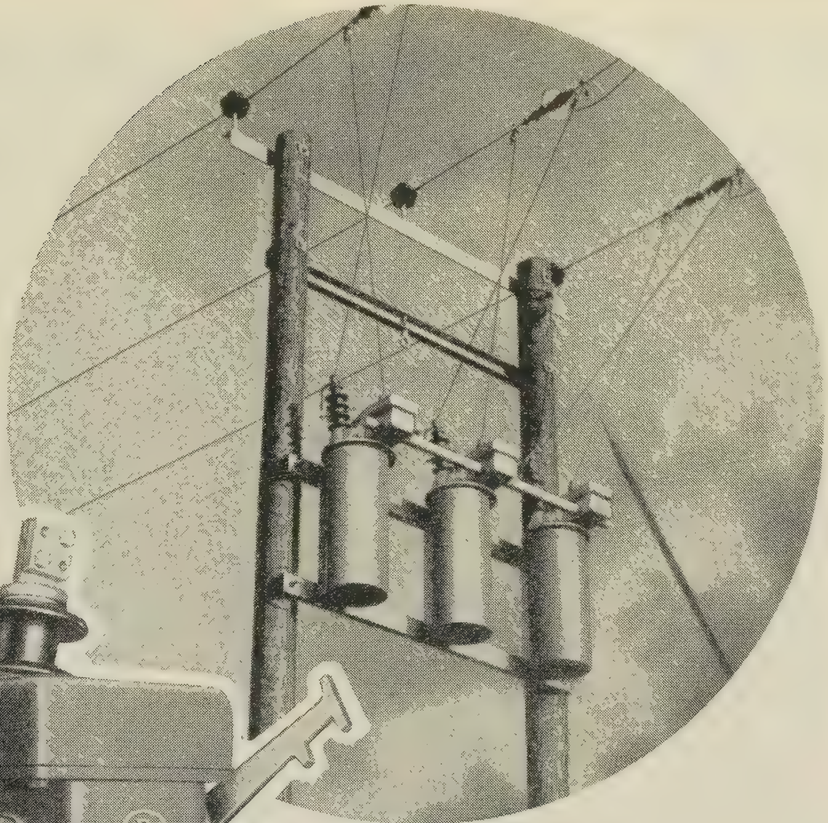

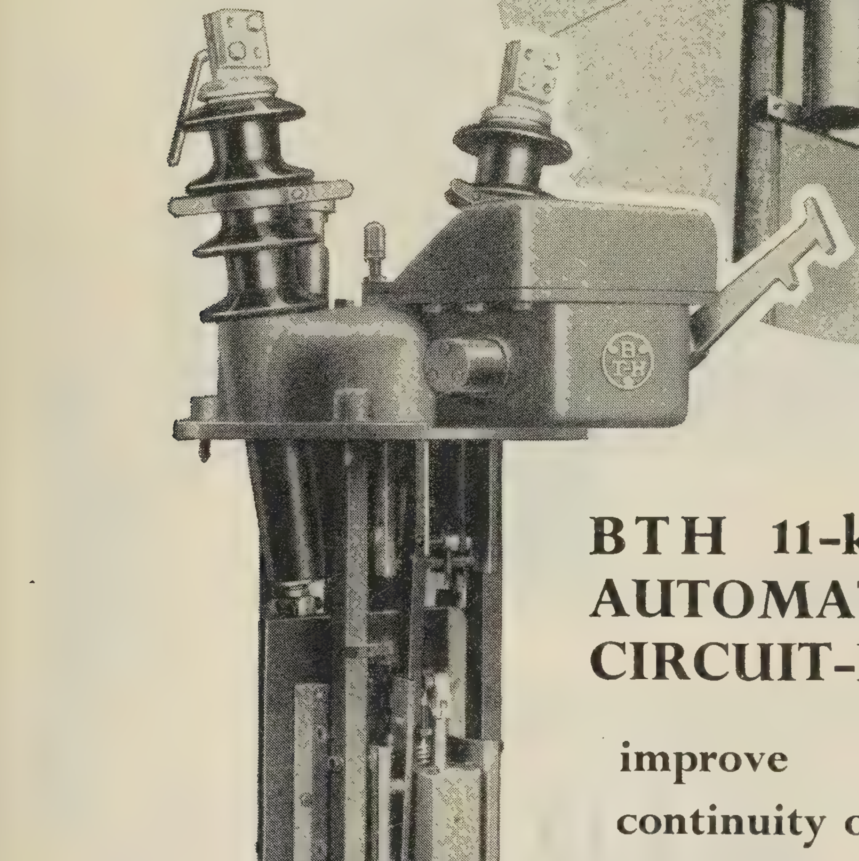

INDEX OF ADVERTISERS

THE PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 105. PART A. No. 20. APRIL 1958

DISCUSSION ON 'AGE AND THE INCIDENCE OF FIRES IN ELECTRICAL INSTALLATIONS'*

Before the SOUTHERN CENTRE *at* HOVE *7th November*, 1956, *the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM *11th March, the* NORTHERN IRELAND CENTRE *at* BELFAST *9th April, and the* SOUTH-WESTERN SUB-CENTRE *at* PLYMOUTH *16th May*, 1957.

Mr. H. W. Swann (*at Hove*): Not everyone could draw the relevant conclusions from statistics as the author has done. The paper is timely and important because since 1946, when the author quoted the fire risk as 10% of all causes, it has advanced to 14% in 1954, or 12000 electrical fires in 84500. It has been estimated that if the growth continues at the same rate 22000 electrical fires per annum might be expected by 1975.

The policy of striving to provide low-impedance earth paths, so that fault current can attain maximum values for clearance by overload devices, is wrong in principle and cannot continue indefinitely as consumer demand increases.

Mr. C. Freeland (*at Hove*): Most of us know, qualitatively and therefore rather vaguely, that old equipment is less reliable than new, and quantitative results confirming that deterioration tends to remain gradual and that equipment which has given satisfactory service is unlikely to fail suddenly are comforting.

The author rightly emphasizes the necessity of avoiding a protracted investigation by making several assumptions and neglecting many factors which might affect results, one of these being the question of extensions to existing installations. Many early installations were for lighting only, being extended at various dates, and each time there would be some disturbance to the existing wiring which might cause damage to brittle insulation and increase the risk of faults and hence of fire. It would be interesting to know whether many fires have followed closely on such extensions and also whether the author thinks his investigation might have been materially affected if the dates of known extensions had been considered.

The figure of 10% of all fires in buildings attributed to electrical causes includes, I understand, fires attributable to the use, or rather misuse, of electrical appliances as well as to defects in electrical equipment. A proportion of this figure could reasonably be assessed as 'hot substances', e.g. hot-plates of electric cookers, electricity merely being the producer of the heat. I am informed that truly electrical fires due to defects in electrical equipment of all types would be nearer 4% than 10%, whilst those due to defects in permanent installations would probably be only slightly over 3%. These percentages, however, will increase as the use of electricity increases relative to other sources of heat.

Mr. V. C. Manley (*at Hove*): At one time consumers' services were protected by a 15 amp fuse, whereas with the increased loading it is frequently necessary to install fuses of 100 amp capacity, and the uncertainty of the fuses operating on an earth leakage on an installation in many cases is due to the high resistance of the return path back to neutral.

I have been concerned for many years with the multiple-earth system, whereby the consumers' earth is bonded in every case to the Board's neutral, and I think that this system, if generally adopted, would go a long way to reduce fire and bad earth leakages, as the earth leakages would become short-circuits and the protection should operate. I should like to have the author's opinion on this.

Mr. T. G. Partridge (*at Hove*): In connection with the deleterious effects of moisture on wiring installations I would like to mention osmotic action, which is always active as a source of importing moisture into all installations on d.c. supply. My own experience in Central London in the late 1920's and the 1930's is that many old installations on 200-volt d.c. mains showed a very marked improvement when changed over to the 230-volt a.c. system. I would ask the author whether he can state from the large number of cases he has cited how many were on d.c. supply as against those on a.c. mains. My own belief is that the incidence of fire risk due to moisture will be greatly reduced as more and more installations are changed over from d.c. to a.c. supply, and osmosis is thus gradually wiped out.

Mr. F. Furlong (*at Hove*): Ascertaining the correct cause of a fire is as important to a fire brigade as a correctly rated fuse is to an electrical installation, for it is only by knowing how fires start that recommendations can be made to avert further occurrences.

In many instances the cause of a fire is not clearly evident, especially when serious damage has resulted from the fire, and only by the process of elimination can it be found. In such cases a detailed study is made before any clearing up or salvage work is commenced, and the services of the brigade's fire prevention officer are called for. This officer is selected for his technical knowledge and receives special training at the Fire Service College, which has at its disposal technicians and scientists from various Government Departments and large industrial concerns for instructional purposes. In addition, two other facilities for obtaining technical advice are available to the fire brigade, namely the honorary fire observers, who are professional men not directly connected with the fire brigade but who are prepared to advise on technical matters should the occasion arise, and the Joint Fire Research Organization.

Chief fire officers frequently use these two approaches when

* GOSLAND, L.: Paper No. 1938 U, January, 1956 (see 103 A, p. 271).

the cause of a fire is in doubt, and failure to reach a satisfactory conclusion will result in the cause being returned as 'unknown'.

You will see, therefore, that determining the cause of a fire is not a hit or miss affair, as may be thought by some. We who serve in the fire brigades and witness the enormous loss created by fire each year, with its associated tragedies, are continually striving to prevent them occurring.

Mr. J. A. Robbins (*at Birmingham*): I should like to emphasize the point made in the paper that earth-leakage currents seem to constitute a major fire hazard. Unfortunately, normal overload protection cannot distinguish between healthy currents and earth-fault currents, and as a result interest has been focused during the past few years on the application of the current-balance type of earth-leakage circuit-breaker to this class of installation. I would be interested to know the author's views on the degree of sensitivity he would consider suitable for this class of equipment. Manufacturing practice, both in this country and on the Continent, appears to favour sensitivities ranging between 0·5 and 2·5 amp out-of-balance, depending on the nominal current rating of the circuit being protected.

Higher sensitivities may be achieved, but the equipment then becomes much more costly, and, in view of the analysis of the position contained in the paper, I would consider it very doubtful whether such high sensitivity and increased capital expenditure could be justified.

It could be argued that a high degree of sensitivity, of the order of milliamperes, would give protection against fires due to leakage attributed to moisture, but, as the total number of fires caused by moisture only amounted to 46 out of the total of 1 100, and in addition this figure of 46 was subject to some reservations, this line of argument would hardly seem very strong.

It is interesting to note the high percentage of fires associated with service equipment which appear to be attributed to fuses, fuse-boards, etc. In addition I am surprised that the author does not consider overloading on circuits a major cause of fire risk, particularly as a booklet on 'Electrical Fire Risks' issued by the Fire Protection Association specifically states that 'Many fires have been caused by protective gear of incorrect rating, especially fuses'. Parallel work carried out on this subject in America, summarized in *Edison Electric Institute* Publication No. R-9, quotes a figure of about 16% of all fuses over-fused and 2·7% bridged. Even if overloading of cables in such over-fused or bridged circuits might not be perhaps the primary cause of a fire, deterioration of insulation, due to sustained overloading in the past, might well be a major concealed contributory cause. In the past, the more commonly used circuits in this country could stand quite a degree of over-fusing, as tacitly acknowledged by the fairly recent uprating of 3/·029 in and 3/·036 in cables. I would therefore be interested to know the author's opinion of the likely effect of over-fusing on circuits wired to the new current ratings, particularly in view of his comments in the paper regarding abuse of cartridge fuses. It would appear that an excellent case could now be made for the use of circuit-protection devices, such as miniature circuit-breakers, which have fixed unadjustable time-current characteristics.

A final point brought out in the American survey was that approximately 40% of all electrical fires in America are due to motors chiefly of under 1 h.p. rating, and whilst this is outside the strict scope of the present paper, I would be interested in the author's comments, particularly as the percentage of all fires attributed to electrical causes seems to have risen from the 10% in 1946, quoted in the paper, to about 18% in 1954.

Mr. R. A. Joseph (*at Birmingham*): It has been suggested that the irresponsible type of contractor who was so much in evidence after the war has now disappeared. I think, however, that a careful watch must still be kept on their activities. I imagine that some of the troubles on post-war installations have been due to the 'Do it Yourself' articles in magazines. The only real answer to this problem seems to be compulsory registration of contractors and operatives, and this paper may assist us in assessing the necessity for such registration. I doubt if the paper gives us sufficient evidence to make a final decision, but I certainly think that Mr. Gosland's figures show the need for a much more detailed investigation, and I hope that further work will be done.

A high percentage of fires are attributed to current leakage. Has it been possible to trace any difference between the performance of p.v.c. and v.r. cables in this respect? A p.v.c. cable has a lower electric strength but, unlike the braiding on v.r. cable, does not hold water.

I am convinced that embrittlement of rubber insulation causes more trouble than the figures suggest, and I think that much premature embrittlement occurs because of inadequacy of wiring and resultant overloading.

I am not clear to what extent the author's figures are based on fires in domestic premises only. Can he give separate figures for commercial and industrial installations?

The use of current-balance circuit-breakers has been suggested to clear circuits with an earth leakage, but if these are too sensitive in operation they will become a nuisance and there will be a danger of their being rendered inoperative by unskilled users. I am surprised that there is no mention in the paper of fires caused by faulty control-gear on fluorescent-lighting fittings mounted directly on the ceiling. I have seen trouble caused by this and would imagine that it might occur quite frequently.

Mr. H. B. Mellor (*at Birmingham*): Regarding the difficulty in obtaining information on the incidence of faults on installations, I consider that much useful data could be obtained from the following sources: assisted wiring schemes carried out by local authorities approximately 25 years ago, municipal housing schemes, and later prefabricated houses.

In these examples large numbers of installations were carried out to the same specification and covered various types of wiring systems.

Some years ago I carried out an investigation on faults in various types of installations and, ignoring those which are common to all installations; the following came to light:

(i) Conduit installations: crowding of v.r. cables and ingress of water due to faulty plumbing or protection caused earth faults.
(ii) T.R.S. installations: earth faults caused by trapping or pressure of bare earth wires on cable cores behind plugs on skirting boards.
(iii) Lead-covered installations: faults caused by nicked conductor insulation when removing lead sheath.
(iv) Capping and casing: if undisturbed, a very sound installation but dangerous if dampness present or faulty plumbing.

Regarding the incidence of fires due to gas piping and earth faults, this would seem to be due to the older houses, which originally had gas lighting and later changed to electric lighting. Gas-pipe runs and loose floorboards formed easy runs for wiring, and the gas pipes were not isolated in all cases.

A mention has been made of incoming service equipment. I consider this should be inspected more often, as, in older property, it is usually in cellars or similar situations.

Mr. C. B. Cox (*at Birmingham*): In view of the large incidence of fires caused by faulty earth conductors, I should like to have the author's opinion on the advisability of the use of the neutral conductor as the earth conductor.

Mr. C. W. Westwood (*at Birmingham*): In considering the relative incidence of fires arising from defects in fittings and fixed wiring, it should be borne in mind that, whereas fittings are not infrequently replaced over a period due to damage or obsolescence, the replacement of fixed wiring will, on account of cost and inconvenience, often be delayed until a failure occurs. The

fixed wiring should consequently have as long a prospective life as possible, and, since it is known that natural-rubber-insulated cables will suffer deterioration, particularly at terminations, over a period of, say, 30 years, the author's views on the desirability of using either synthetic-rubber- or plastic-insulated cables would be welcomed.

Mr. F. Atkinson (*at Birmingham*): Some mention has been made of the embrittlement of rubber insulation due to age or overloading of conductors. I should like to know if the author has noticed any trend towards longer safe life of installations dating from about 1930, when a revolutionary change in the technique of manufacture of rubber-insulated cables was introduced. I refer to the use of anti-oxidants which have the effect of reducing embrittlement due to self-vulcanization.

On the method of investigation, it would appear that valuable information was lost through the delay in inquiries reaching the Area Boards. Where the fire had already been reported to the Board there was no difficulty, but in many other cases had the Board had the opportunity to carry out a detailed examination very much more useful information would have been obtained. Could there not be some local arrangement whereby the Board is advised directly, and thus enabled to report within, say, 48 hours of the fire?

In view of the importance of the investigation, it would appear desirable to appoint a full-time officer from each Board to complete the detailed questionary within a few hours of occurrence. On the basis of 2000 alleged electrical fires a year it should be possible to visit each case within 48 hours. This suggestion would also assist in obtaining a more uniform and higher standard of reporting.

Mr. H. F. Marshall (*at Birmingham*): Regarding the comparatively high incidence of fires attributed to post-war installations, I would suggest that at the end of the war there was a tremendous back-log of domestic installation work, which the reputable electrical contractors could not handle immediately. Many unskilled, semi-skilled, or unscrupulous fellows jumped in overnight and called themselves electrical contractors, for there was—and still is—nothing to stop them.

The National Inspection Council has been mentioned. This is an excellent body and I am sure that we all wish it every success. We should remember, however, that its Roll of Approved Contractors will be, by and large, a list of reputable contractors whose work would be good in any case. Unfortunately the Council does not have any power over the other type of contractor, who will continue to carry out shoddy work and maybe help to maintain the high incidence of fires.

Mr. P. Hart (*at Birmingham*): In view of the number of fires caused through contact between an earth-continuity conductor and a gas pipe, I suggest it is advisable to insulate the earth-continuity conductor throughout its length or at specific areas in the vicinity of gas pipes.

In Table 10 of the paper, reference is made to various types of cables, but there is no mention of mineral-insulated copper-sheathed cable. Has the author any knowledge of fires connected with this type of cable?

In my opinion, the best way to avoid fires caused by electrical faults is by periodical inspection and testing—preferably by passing a current of perhaps 15 amp through the earth conductor.

Mr. J. R. W. Murland (*at Belfast*): The author is to be congratulated on his honesty in stating so clearly the limitations and possible inaccuracies of his basic data; such statements are too often omitted from papers like this.

I am, however, very concerned about the origin (and hence the ultimate objective) of the paper. As I see it, the author set out to answer an unanswerable question, and further, even if the answer could be obtained, it would serve no practical purpose. The question is unanswerable because the combination of many factors which is termed 'age' cannot be expressed quantitatively in years.

Even if we knew a specific number of years after which the fire risk exceeded a stated probability, I think there is little we could do. Central government is unlikely to legislate when such a large number of voters would be affected, supply authorities can do little more than they do now without exceeding their powers, and insurance companies will probably continue to base premiums on actuarial rather than technical considerations. There is, of course, a parallel in the case of old steam boilers which are not taken out of service at any fixed age however technically desirable this might be.

The disturbing thing is that the researches described by the author are to continue. I would like to ask in what direction they are continuing and with what object. If the object is different from that given at the beginning of the paper, it should surely be restated in more accurate and appropriate terms.

Mr. J. H. Phillips (*at Plymouth*): The general conclusion of the paper that the fire risk increases with the age of the installation is what we would have expected, and this, of course, takes into consideration all parts that go to make up complete installations. No doubt many of us are surprised by the number of fires attributed to services and to distribution boards, but I am particularly interested in those associated with defective wiring, analysed by type of wiring in Table 10. Group C, which covers 21·8% of the total population covered by the survey, accounted for 35% of the fires caused by faults in wiring, and, what is still more surprising, 18 out of the 73 fires which gave this percentage were on t.r.s. installations. Are we correct in assuming that in group C there are more t.r.s. installations than in any other group? Is this group more predominantly rural?

If we take the distribution of types of wiring over the 210 installations where fires were caused by defects of this type, we find that the largest proportion (26%) occurred in connection with vulcanized rubber in conduit, and this is to be expected because conduit wiring has been used over the whole of the survey period and is, of course, susceptible to earth faults and to fortuitous earth connection with composition gas pipes, etc. 22·4% of the faults are in the class where the type of system was not known and 18% on lead-covered vulcanized-rubber wiring, which was the system in general use (after conduit) up to, say, 1930–32. This again demonstrates the increase of fire risk with increase of age. We are left with t.r.s. wiring as the only remaining system with a high percentage, namely 11%, or 23 out of 210 fires, where the fault was in the wiring, occurred in t.r.s. systems, and this type of cable has only been in general use since about 1930.

T.R.S. cable provides insulation to phase, neutral and earth conductors and a degree of mechanical protection. Earth or short-circuit faults are confined within the sheathing; there is no possibility of contact with gas pipes, etc. If faults were due to short-circuits or earths caused by driven nails, then their persistence to the fire stage could only be due to non-operation of the protection (fuses for short-circuits and some of the earth faults), but, if the installations were rural, where full use has been made of t.r.s. systems, then earth faults may have been associated with non-operation of earth-leakage circuit-breakers. This is not borne out by the results shown in Table 9, unless this refers only to occasions when there were no other faults on the installation.

In this area, with its large number of rural consumers, we are particularly interested in this angle: from 1930 up to 1952 practically all rural work was carried out in t.r.s. Can we expect faults in this type of wiring, and will p.v.c. be immune from these types of faults or will it be similarly affected?

Can the author make available to the supply industry a more detailed analysis of wiring faults?

Mr. C. G. Agg (*at Plymouth*): As one responsible for installation, testing and inspecting in Plymouth, I should like to present some facts in respect of fires which have taken place here. The information was obtained from the Plymouth Fire Brigade, and the figures refer to the year ending 31st March, 1957:

Total number of fires which occurred in the city precincts, 300
Number attributed to electrical causes, 15
Number associated with the fixed wiring, 8
Number associated with ceiling pendants, etc., 3
Number in fixed motors (all refrigerators), 6

In each of the eight fires associated with fixed wiring, gas pipes were involved. Two of the installations were 30–35 years old and five were 20–30 years old.

We also had in Plymouth one occurrence similar to that related in Section 7.1. In our case, a fault was transmitted from the outside network through the consumer's earth wire to the gas pipe. Fortunately, no fire was caused, but there was a smell of burning rubber traced to the fact that some 15 amp were continually passing through an earth-continuity conductor which consisted of 3/·036in cable.

Two points interest me in regard to the large incidence of fires in the older type of premises and those in the post-war premises. In the case of the older house, built prior to 1925–26, there was much more possibility, when the house was wired, of the permanent wiring coming into contact with the gas pipes. In the second case, is it not possible that the higher average loadings obtaining in post-war houses contribute to the failure of fittings?

I would comment on the large number of fires caused by faults on refrigerator motors. I suggest that this may be due to two main causes: (i) the operation of the refrigerators in confined spaces, and (ii) the under-powering of the equipment. Either would be demonstrated by the fact that a refrigerator has to work its hardest at times when the ambient temperature is high, e.g. a butcher's refrigerator full of meat, working over a holiday week-end, say in August. I am sure that each of these causes contributed to the number of fires.

Finally, may I make a plea for good and careful workmanship in respect of all electrical installation work. A factor of considerable importance is tidiness when erecting installations in confined spaces. Wood shavings or dry debris of an inflammable nature left about will kindle easily. All contacts should, of course, be tightened properly. In addition, careful attention must be paid to earthing because, although, as the author says, fires may occur even with good earthing, it is obvious that many more must have been avoided because the metal sheathing had been properly connected to earth.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. L. Gosland (*in reply*): Unfortunately, the data available are insufficient to permit a satisfactory reply in many instances. With a paper such as the present, it is important that the author should draw a clear distinction between conclusions from the information at his disposal and his own opinion as to probabilities, confining himself to the former. The paper included practically all the available information, so that little that is factual can be given in reply to the discussion.

Several speakers raised questions of the relative merits of various types of wiring. Mr. P. M. Hollingsworth gave a good summary of the present position in his contribution to the London discussion.* Of Mr. Phillips's interesting analysis of Table 10, it can be said that most of the cases attributed to t.r.s. installations occurred in a single urban area. It is possible that many of the wiring defects arise from abuse near terminations and are thus not specific to the type of insulation. Mr. Freeland questions the effect of ignoring the presence of extensions: it is likely that this has weighed against the oldest installations, but it is not known that many fires followed closely on extensions. He also indicates the care taken over attribution of causes. I believe that in addition there is now usually very good liaison between fire authorities and Area Boards: when the survey started in 1950 there was room for the improvements suggested by Mr. Atkinson, but the situation now seems very much better. The attribution of causes is analysed with some care by the Joint Fire Research Organization, and the figures mentioned by Mr. Freeland can be extracted. I have no certain information on the number of cases covered which occurred with d.c. supply, but would agree that elimination of direct current may reduce the importance of moisture as a cause of fire. It is probable, however, that even with alternating current, moisture is a rather more frequent cause than Mr. Robbins suggests. Care was taken to suggest in the paper that the rarity of attributions to moisture was probably due to the fact that it is difficult to detect.

The apparent discrepancy between the figures given by Mr. Swann and by Mr. Robbins for the incidence of electrical fires in 1954 is probably due to the fact that the former treats of all fires in the United Kingdom, the latter of fires in buildings in England and Wales. It is not possible, as Mr. Joseph requests, to give separate figures for commercial and industrial installations. The figures in the paper are based on fires in buildings of all uses: a small proportion were commercial premises, very few industrial, possibly because industrialists deal with most of their own minor outbreaks.

Mr. Swann and Mr. Robbins draw attention to the importance of specific protection against earth leakage, which should be particularly helpful when there are earth faults of relatively high impedance and thus normally when load currents are high. The answer to Mr. Robbins's question on degree of sensitivity required depends on the answer to another: do leakage paths usually fall to a resistance of less than 100 ohms before they dissipate enough energy to start a fire? I confess that the information in the paper is not very helpful on this point. Given overload protection only, use of the neutral for earth return, according to protective multiple earthing regulations, is to be recommended when earthing is difficult.

Mr. Agg suggests that the greater incidence of fires in older installations may be largely due to the greater probability that they co-exist with gas carcassing. This factor has been examined (see Fig. 8) and does not in fact appear to have influenced the results.

I have some sympathy with Mr. Murland, who suggests that an answer to the question posed at the beginning of the paper is impossible, and, even if possible, useless. Some defence against his first point is given in the reply to the London discussion. As to the second, central action seems improbable, but there are an increasing number of occasions on which individual decision is required and can be influenced by proper consideration of co-ordinated general experience.

Space does not permit comment on the many interesting points of detail brought out, nor more than a general expression of agreement with those speakers who have advocated better craftsmanship in the original installation and appropriate inspection throughout its life.

* *Proceedings I.E.E.*, 1956, 103 A, p. 271.

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D.C. WINDER DRIVES USING MERCURY-ARC RECTIFIER/INVERTERS

By L. ABRAM, B.Sc.(Eng.), J. P. McBREEN, Associate Members, and J. SHERLOCK, B.Sc.(Eng.).

(*The paper was first received* 22*nd October, and in revised form* 13*th December*, 1956. *It was published in February*, 1957, *and was read before the* NORTH-WESTERN CENTRE 5*th March, the* UTILIZATION SECTION 14*th November, the* SHEFFIELD SUB-CENTRE 20*th November, the* WESTERN UTILIZATION GROUP 25*th November, and the* NORTH-EASTERN CENTRE 9*th December*, 1957.)

SUMMARY

The high efficiency of mercury-arc-rectifier equipments would appear to make their use desirable on winder drives, on which efforts are continually being made to reduce hoisting costs. After outlining the requirements of a winding engine, the paper briefly describes a.c. and Ward Leonard drives, discusses their advantages and disadvantages, and compares them with a rectifier drive. The advantages of the latter led to the installation of such an equipment at Monk Bretton No. 3 Shaft, and the various rectifier connections and the methods of changing from rectification to inversion are considered. Various aspects of grid control and transformer design are discussed, and some rectifier faults are described, together with the protection provided against such faults. The winder is provided with closed-loop speed control and the system used is described. A comprehensive series of tests was carried out on the installation and the results obtained are illustrated.

(1) INTRODUCTION

Although mercury-arc rectifiers have been employed in traction and rolling-mill drives fairly extensively, their use for winding-engine control has been very limited. The first installation in which the d.c. winder motor was supplied from a rectifier was at Zollern No. 2 Pit in Germany,[1] where the rectifier replaced a motor-generator set which had been in operation for 30 years. Consideration was also given to this application of mercury-arc rectifiers in France and in the Soviet Union, but it is not known[2,3] whether any installations are in operation in these countries. The first installation in Great Britain, which has been in operation since the early part of 1955 at Monk Bretton No. 3 Shaft, is described in the paper.

(2) WINDING-ENGINE DUTY

The problems associated with this application of mercury-arc rectifiers will be better understood if consideration is first given to the duties imposed by a winding engine.

(2.1) Normal Cycle

A winder is generally required to raise a given load according to a designed speed/time cycle, which may be divided into the following four intervals:

(*a*) Period for accelerating the masses to the required speed.
(*b*) Period of running through the shaft at the required speed.
(*c*) Period for the masses to be retarded and stopped.
(*d*) Stationary period during which the load is being removed from the conveyance.

Thereafter the next winding cycle is commenced, in which the direction of wind will be reversed. Typical examples are shown in Fig. 1, which also indicates the torque requirements during the cycle. It will be noted that the torque can either remain positive during the whole cycle or can change from positive to negative at some time during the cycle.

The authors are with the Metropolitan-Vickers Electrical Co., Ltd.

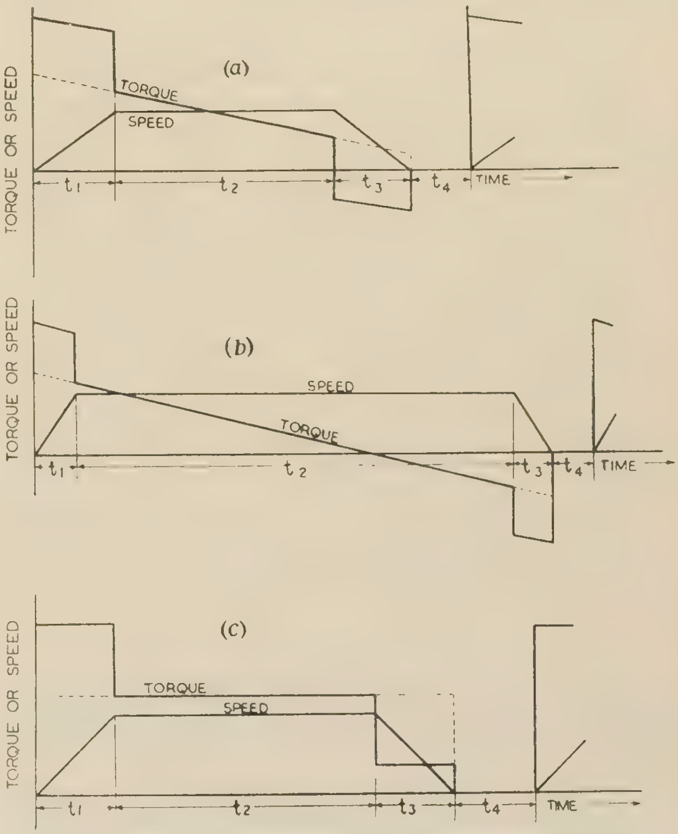

Fig. 1.—Typical speed and torque cycles.

t_1 = Acceleration time.
t_2 = Full-speed time.
t_3 = Retardation time.
t_4 = Decking time.

(*a*) Drum winder.
(*b*) Deep drum winder.
(*c*) Koepe or friction winder.

(2.2) Auxiliary Duties

In most cases the winder may be called upon to perform duties other than that for which it is principally designed. It is often required to raise or lower men or materials, and shaft examination and rope inspection have to be carried out at regular intervals. In addition, manoeuvring operations may be required during which only small movements of the engine at low speeds occur. Such operations are an essential part of the decking sequence when the conveyance is a multi-deck cage and the different decks have to be positioned successively at the landing level.

(2.3) Closed Loop Control

The policy of concentrating winding in a comparatively few main shafts which are used to the full has led to the development of closed-loop speed-control systems which enable the winding cycle to be maintained more precisely than is possible with normal manual control.[4]

Two systems exist for operating electric winders with closed-loop control, namely automatic operation, in which the wind is initiated by the operation of a pushbutton and the remainder of the cycle, including the decking, is completed automatically, and cyclic manual operation, in which the driver has control of the winder and selects the running speed, while acceleration, deceleration and the maximum speed approaching the bank are subject to preset limits. In the normal coal winding cycle the lever is thrown over to full speed and the system accelerates under acceleration limits to full speed. After the full-speed run through the shaft, the winder is decelerated by a cam reduction of speed in accordance with the cycle.

(2.4) General Requirements of Winder Control

The speed and torque requirements may thus differ quite appreciably from the normal cycle, and a winder control scheme must therefore be capable of dealing with loads up to the maximum at all speeds in either direction up to the designed full speed.

Of the two systems employing closed-loop principles, the second calls for more precise control, but both systems must, in greater or lesser degree, meet the following requirements:

(*a*) At creep speeds (approximately 5% of the maximum) sudden load changes such as occur when decking must not cause speed changes greater than $\pm 10\%$ of creep speed. This means that changes from no load to full load at top speed must cause only $\pm\frac{1}{2}\%$ speed change.

(*b*) Acceleration control must maintain the accelerating period constant to $\pm 10\%$ of the no-load figure for raising and lowering loads. This figure also applies to deceleration under deceleration limits.

(*c*) Deceleration when following the cam curve under speed control must be within $\pm 5\%$, and closer control than this is desirable. This also calls for an adequate speed of response from the control system. It is not sufficient to have a highly accurate control if the response is too sluggish to fulfil this requirement.

(3) ELECTRIC WINDER DRIVES

In the past, electric drives for winders have been provided by using either a 3-phase induction motor or a d.c. motor supplied from a motor-generator set and controlled on the Ward Leonard principle.

(3.1) A.C. Motor Drive

The 3-phase induction motor with wound rotor has proved attractive because of the relative simplicity and robustness of the machine and the absence of commutators and the maintenance associated with them. However, the auxiliary gear required to control the direction of rotation and speed of the motor is fairly extensive. With this type of drive the motor is connected to the incoming supply through reversing contactors which determine the direction of rotation, the required contactor being selected by appropriate movement of the driver's control lever. The speed is determined by controlling the resistance inserted into the rotor circuit of the machine.

(3.1.1) Rotor Resistances.

The rotor resistance may take one of two forms. If a liquid regulator is used the resistance is determined by the distance between fixed and moving electrodes, but the resistance can vary over a wide range depending on the temperature and strength of the electrolyte. Although an infinitely variable resistance is obtainable, the mass of the moving electrodes is generally so great that hydraulic servo-mechanisms have to be introduced to reduce the physical effort required on the driver's control lever. These servo-mechanisms, or 'accelerating devices', are also used to control the rate at which the resistance may be varied so as to prevent an unduly high torque being imposed on the winder.

Alternatively, grid resistors may be used, the amount of resistance in circuit being selected by means of rotor contactors. The variation of resistance with temperature on these units is small, but unless a large number of contactors is used, the speed can be controlled only in steps. Since the rotor voltage is limited, the rotor current is heavy, particularly with large winders, so that the contactors are fairly large and for economic reasons the number of steps available is limited.

(3.1.2) Reduced Speed Running.

One of the main disadvantages of the 3-phase induction motor is that, when running at reduced speeds with resistance inserted into the rotor circuit, a considerable portion of the power drawn from the supply is dissipated in the form of heat in the rotor resistance. This equipment must thus be suitably rated for such duties, and the efficiency of the installation is greatly reduced. Furthermore, it is not practicable to increase the maximum resistance to a value greater than that which would produce approximately 30% of full-load torque at standstill. This discontinuity in power makes light-load low-speed running difficult.

(3.1.3) Electrical Braking.

Another major disadvantage of this type of drive is that regenerative braking can be achieved only when running at super-synchronous speed, i.e. at speeds in excess of the normal full speed of the winder. Thus, retardation of the winder or running at reduced speeds with descending loads can be performed only by using other forms of braking. Such braking can be obtained electrically by reversing two of the phases on the motor stator, but this reverse-current braking is inefficient, since the power drawn from the line and the heat to be dissipated in the rotor resistance are greatly increased.

Some of these disadvantages have been overcome by the development of d.c. injection or dynamic braking,[5,6] in which the machine is made to operate as an alternator with direct current injected into the stator and the rotor resistance used as a load. Considerable saving in power compared with reverse-current braking is achieved, but the energy stored in the moving parts is dissipated as heat in the rotor resistance and is not returned to the supply.

(3.2) Ward Leonard Drive

Most of these disadvantages are overcome by the use of a d.c. motor to drive the winding engine. The motor is provided with a shunt field excited from a constant-voltage d.c. supply, while the speed of the motor is controlled by varying the voltage applied to its armature. This voltage is derived from a d.c. generator running at substantially constant speed, and is controlled on the Ward Leonard principle by control of the generator field current. The direction of rotation of the motor is determined by the polarity of the applied armature voltage, and as this can be reversed by reversal of the generator field current, the motor armature is generally solidly connected in series with the generator armature.

(3.2.1) Direct-Coupled Drive.

The d.c. motor drive lends itself to direct-coupled drives far more readily than does the 3-phase induction motor, as the latter almost invariably involves a geared drive. The possible omission of gears which have to be carefully manufactured, erected and maintained, and of the associated additional bearings, is a strong point in favour of d.c. drives.

(3.2.2) Generator Field Control.

The power involved in the generator field circuit is comparatively low and the size of the control equipment is much reduced. Various systems have been evolved for controlling the field current, the more recent of these employing closed-loop

principles designed to reduce the inherent speed regulation of the system. Even without this closed-loop control, the variation of speed with load is not as great as for the induction motor. Furthermore, the change from motoring to regenerating conditions can be achieved smoothly at any speed without the operation of contactors, either by a slight increase in the motor speed or by a small reduction in the generator field current. Thus reduced-speed running does not imply the great reduction in efficiency inherent in the induction-motor drive.

(3.2.3) **Motor-Generator Sets.**

The d.c. generator forms part of a motor-generator set, being driven by an a.c. motor. This driving motor is, in many cases, a synchronous machine, the power factor of which can be controlled so as to reduce the apparent power demanded from the supply system. In some cases a flywheel is included in the set and some form of slip control is employed, so that the flywheel is used to reduce the peak loads imposed on the supply system.

Besides these advantages, however, the motor-generator set also has serious disadvantages, mainly economic, which constitute the main drawback of this type of drive. The initial cost of the motor-generator set, special foundations and buildings is not inconsiderable; there is also the extra maintenance cost. In addition, the light-load losses of the set, particularly where a flywheel is used, are appreciable, and with a winder where there are lengthy idle periods when no winding is being carried out, these losses can account for an unduly large proportion of the power consumed.

(3.3) **Rectifier Drive**

It is in order to overcome these disadvantages that consideration has been given to the use of mercury-arc rectifiers. Not only are rectifiers static items of equipment requiring little maintenance, but they also do not require special foundations and generally occupy less space than a motor-generator set, so that they can be situated in the winder house. The associated rectifier transformer can readily be manufactured suitable for outdoor use, so that no special buildings are required.

The variable output voltage required to control the speed of the motor over its full range is obtained by means of grid control, the general principles of which are well known.[8,9] The reversal of this voltage and of the current flow through the motor to achieve the changes from motoring to regenerating conditions create problems of control which will be discussed later.

(3.3.1) **Comparison of Efficiency.**

The efficiency of a rectifier-controlled drive is considerably greater than that of either an a.c. or a Ward Leonard drive. This higher efficiency is illustrated by the reduced power consumption for a given winding cycle, several instances of which are listed in Tables 1 and 2. Table 1 shows a comparison between a.c. winders and rectifier winders. In the former it has been assumed that regenerative or dynamic braking is used whenever possible, and the power consumption is thus the minimum that could be obtained. The saving is most marked where much of the winding time is taken up with accelerating and retarding the masses (i.e. in cases 1 and 5).

Table 1

Comparison of Power Consumption on A.C. and Rectifier Winders

Case	Motor rating	Shaft depth	Winding speed	Output per hour	Winds per hour	Power consumption: A.C.		Power consumption: Rectifier	
	h.p.	ft	ft/sec	tons		kWh/wind	%	kWh/wind	%
1	400	381	25·4	180	106	1·95	227	0·86	100
2	450	574	23·0	200	80	2·82	118	2·38	100
3	600	936	15·7	250	41·7	8·15	117	6·97	100
4	1000	1095	15·6	300	60	8·33	128	6·51	100
5	1200	976	46·2	240	87·4	6·48	182	3·56	100

Table 2

Comparison of Power Consumption on Ward Leonard and Rectifier Winders

Case	Motor rating	Shaft depth	Winding speed	Output per hour	Winds per hour	Power consumption: Ward Leonard		Power consumption: Rectifier	
	h.p.	ft	ft/sec	tons		kWh/wind	%	kWh/wind	%
1	1800	2800	40·5	210	35·3	21·6	113	19·1	100
2	2500	2500	50·0	270	50·0	19·1	109	17·6	100
3	2500	4000	50·0	125	35·4	22·3	110	20·3	100
4	2300	3070	50·0	250	20·8	47·0	103	45·7	100
5	4450	6316	52·5	288	24·0	99·0	118	84·0	100

In Table 2 the comparison is between Ward Leonard and rectifier winders, showing that the saving in consumption of the rectifier is also appreciable. These figures have been calculated on the assumption that winding is being carried out continuously. If any idle periods occur, the advantage of the rectifier installation is increased, owing to the higher light-load losses of the motor-generator set. For example, in case 2 the light-load loss of the motor-generator set is 96 kW whereas that of the rectifier and transformer is only 26 kW.

(3.3.2) **Heat Dissipation.**

Another aspect in which the rectifier shows to great advantage is in the heat dissipated from the electrical equipment. This matter is of considerable importance in the deep mines in South Africa, where winders are installed underground and where

ventilation presents many problems. In such cases it is desirable to keep the additional heat dissipated by the winder to a minimum. It had been calculated for a typical 1 800 h.p. winder that the heat dissipation of a rectifier installation would be only 60% of that of an equivalent Ward Leonard installation and as low as 40% of an equivalent a.c. winder.

(3.3.3) **Power Factor.**

With grid-controlled rectifiers the power factor varies roughly in proportion to the reduction in voltage by grid control. At various times suggestions have been made, such as the separate control of alternate phases,[7] to remove this disadvantage, which is the only serious disadvantage of the rectifier when compared with the motor-generator for winder drives, but so far no really practical solution has been devised.

The comparison with an induction-motor drive is, however, quite favourable, the calculated power factor and the apparent-power demand for a 300 h.p. winder for a normal raising duty being shown in Fig. 2. The average power factor for this cycle

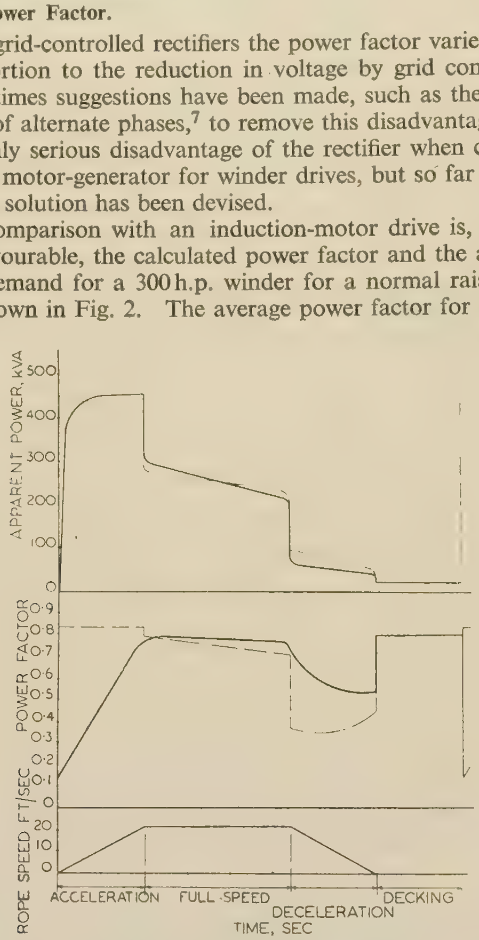

Fig. 2.—Calculated apparent power and power factor during normal winding cycle on 300 h.p. winder.

——— Rectifier winder.
—·—·— A.C. winder.

Calculations allow for a 20 kVA 0·8-power-factor load for winder auxiliaries.

is 0·68 for the rectifier and 0·70 for the induction motor, while the maximum apparent powers during the cycle are 455 and 450 kVA respectively.

(4) RECTIFIER/INVERTER

The advantages of the mercury-arc-rectifier drive led to its installation at the No. 3 Shaft of Monk Bretton Colliery, particulars of which are listed in Section 10.1. The installation consists of a drum winder driven through gears by a d.c. motor supplied from a mercury-arc rectifier.[11] The speed of the winder is controlled on closed-loop principles and certain overriding limits are incorporated. The winder is arranged to be manually controlled, so that the engine driver selects the direction of wind and the speed, the differentiation between rectification and inversion being achieved automatically. As first installed, retardation at the end of the wind is effected by the driver, but provision is being made for the addition of cam gear, so that the winder will be of the cyclic manual type.

Since this particular installation was in the nature of a development—in fact, it was planned as a simple rectifier drive with provision for inversion as an experiment—certain features are provided which, after the experience obtained, would not be repeated on future equipments. Such features include rheostatic braking by means of grid resistors and contactors selected by the driver's control lever, and special protection of the motor against voltage surges by means of an ignitron loading unit. The former is not now being used, while the latter would be replaced by more conventional surge protectors.

(4.1) Rectifier Power Reversal

Since the mercury-arc rectifier is a unidirectional current-carrying device, one of the first problems requiring attention was that of meeting the winder requirements for reversal of power for regeneration. It is usual to associate the reversal of the direction in which power is being passed in a d.c. system with the reversal of the direction of current, but the same effect can be achieved by maintaining the direction of current flow and reversing the direction of the voltage; this method has to be used with rectifiers. In order to pass power from the d.c. to the a.c. side, i.e. to invert, the current is made to flow when the voltage is negative. At the same time it is necessary to reverse the polarity of the back-e.m.f. of the motor with respect to the rectifier voltage, in order to avoid an effective short-circuit on the d.c. side of the system.

(4.1.1) **'Figure 8' Connection.**

The simplest method of achieving this reversal would appear to be to connect two duplicate rectifiers back to back in what is known as the 'figure 8' connection, as shown in Fig. 3(*a*). For one direction of rotation of the motor, and hence for one polarity of the motor back-e.m.f., one rectifier is phased for rectification and the other for inversion: for the opposite direction of rotation the functions of the two rectifiers are reversed. The arrangement is such that a change from motoring to regenerating takes place smoothly, as in the case of the Ward Leonard drive. The arrangement, however, is expensive, since the total rating of the rectifiers is considerably greater than that of the motor and the construction of the rectifier transformer is complicated by the need for two secondary windings. The cost is, in fact, considerably greater than that of the motor-generator set which it would replace. In addition, the control is more complex than for the alternatives given below, because the two rectifiers have to be simultaneously controlled for rectification and inversion throughout the winding cycle, and, moreover, controlled in such a manner as to prevent large circulating currents.

(4.1.2) **'Figure 0' Connection.**

The cost of the above arrangement can be considerably reduced by making use of the 'figure 0' connection, in which only one rectifier is used and reversal of the back-e.m.f. of the motor is effected by a reversal of the armature connections, as shown in Fig. 3(*b*). For one direction of rotation of the motor, contactors C_1 connect the rectifier to the motor so that current flows in the appropriate direction and rectification takes place, while contactors C_2 are available to reverse the current flow through the motor to permit inversion. For the opposite direction of rotation the functions of the contactors are reversed. The mechanical and electrical duty on the contactors obviously increases with increase in rating, as also does the risk of trouble from switching surges; because of limitations in available contactor design, the practical limit of this connection using armature switching is an armature current of about 1 kA.

Armature switching also suffers from the disadvantage that during the change-over the winder motor is free from control

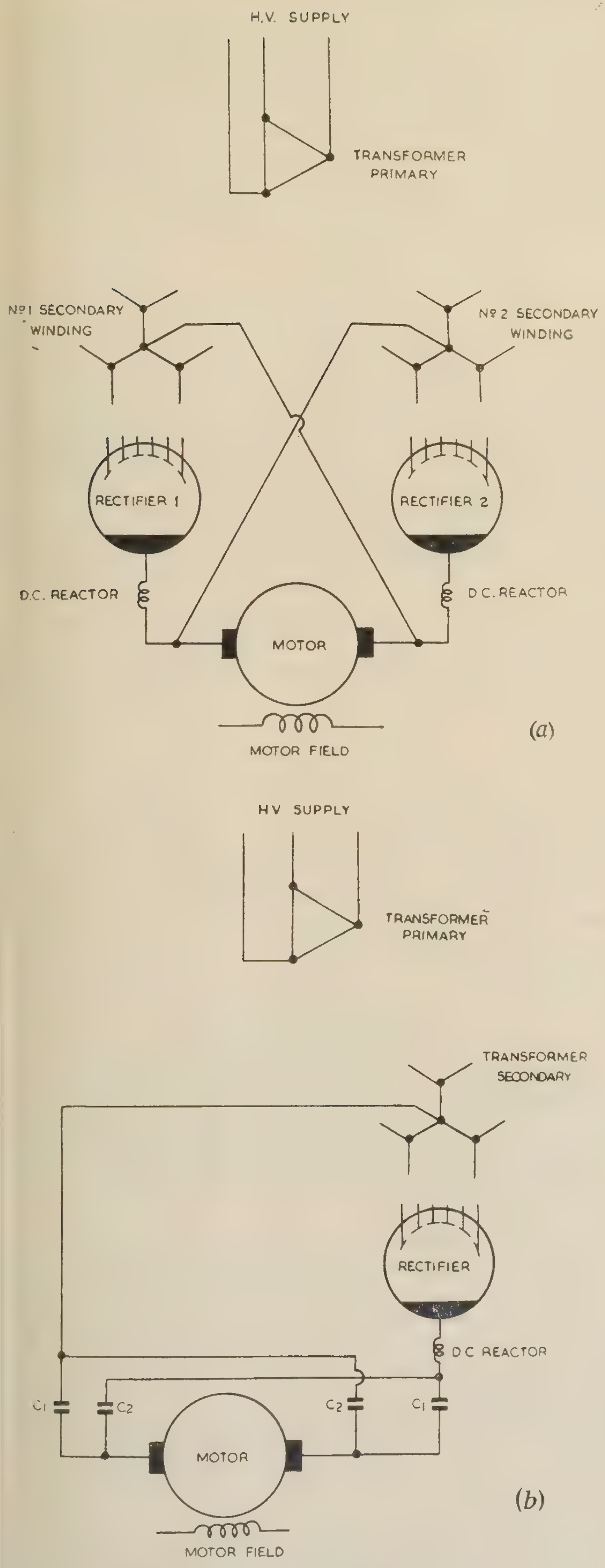

Fig. 3.—Connections of rectifier/inverter.
(*a*) 'Figure 8.'
(*b*) 'Figure 0.'

and with descending loads acceleration under gravity can take place. This is referred to in Section 6.1.1.

Since the Monk Bretton winder has a motor armature rating of less than 1 kA, armature switching with contactors has been used there, but since the present range of contactors puts a severe limitation on the use of the 'figure 0' connection, field reversal has been considered for the larger ratings.

(4.1.3) **Field Reversal.**

With field reversal the connections between the motor and the rectifier are maintained and the reversal of the back-e.m.f. of the motor is achieved by reversing the motor field current. The power involved in these change-over circuits is much smaller than with the previous method, but because of the magnetic inertia of the field system, it is essential to employ field forcing to obtain the reversal in the required time, which is estimated to be a maximum of one second. This will probably mean alterations to the present methods of construction of d.c. motors, but it should present no unsurmountable difficulties.

One important difference between field reversal and armature reversal should be noted here: with the latter, as stated in Section 4.1.2, no control of the winder speed is exercised during the whole of the period in which the reversal takes place. Thus, when the contactors close after the reversal, because of the change in speed due to gravity, a sharp increase in armature current, and hence in torque on the winder, can occur. With field reversal, the motor back-e.m.f. decreases to zero and builds up in the opposite direction during the change-over. Arc suppression is applied to the rectifier while the field current is decreasing, but as soon as the field current, and hence the back-e.m.f., starts to build up in the correct direction, this is removed and grid control is applied. Thus the rectifier voltage builds up simultaneously with the back-e.m.f., and the increase in torque is smooth and controlled throughout. In addition, since control is being exercised as soon as the field current passes through zero, the time during which no control is being exercised is only a fraction of the total time for field reversal. It is therefore felt that this system will give better operating results than those obtained with the Monk Bretton installation.

(4.1.4) **Rectification/Inversion Change-over.**

It will be apparent that the change from rectification to inversion cannot take place without a contactor operation. Some means must therefore be provided for detecting when such a change-over should occur. Ideally, it should be effected whenever the back-e.m.f. of the motor exceeds the voltage from the rectifier, but difficulties in measuring the back-e.m.f. make such an arrangement impracticable. The device which is preferred and has been used at Monk Bretton detects when the actual speed of the winder is greater than the required speed, and under such conditions effects the necessary contactor changes.

(4.2) Grid Control

(4.2.1) **Grid Control for Rectification.**

The current and voltage waveshapes of a conventional free-firing mercury-arc rectifier are as shown in Fig. 4(*a*). The current commutates naturally from anode to anode as the voltage of each succeeding anode becomes more positive, the shaded portion of the voltage wave being the overlap period, when, owing to circuit inductance, both the commutating anodes momentarily share the load.

By interposing control grids between the anodes and the cathodes it is possible to delay this commutation beyond the point where it would naturally occur until later in the cycle and thus to reduce the average d.c. output of the rectifier, as shown

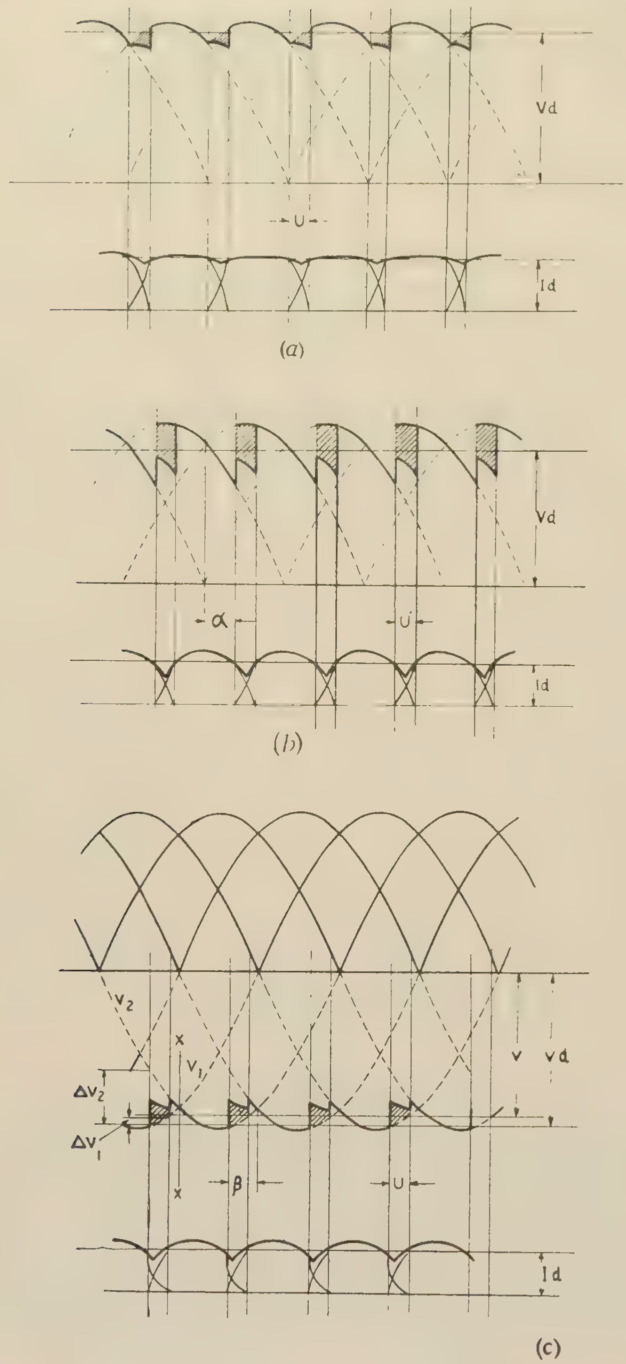

Fig. 4.—Voltage and current waveshapes.

(*a*) Rectifying, free-firing.
(*b*) Rectifying, with grid control.
(*c*) Inverting.

V = Mean inverter phase voltage.
V_d = Mean d.c.-circuit voltage.
I_d = Direct load current.
α = Angle of firing delay.
β = Angle of firing advance.
u = Angle of overlap.

in Fig. 4(*b*). It follows that by infinitely varying this delay it is possible to obtain an infinitely variable voltage from the rectifier.

4.2.2) Grid Control for Inversion.[8, 10]

For inversion, the current must flow when the anode voltage is negative. This is achieved by delaying the firing of the anodes beyond the zero voltage for rectification, as shown in Fig. 4(*c*), which shows that there is an obvious limit beyond which the firing point must not be delayed. Commutation of current between anodes 1 and 2 can be achieved only when Δv_2 is greater than Δv_1. At point X these two values are equal, after which Δv_1 becomes the greater; commutation must therefore be completed before the point X, otherwise a short-circuit occurs. This fixes the maximum value of α, or more conventionally the minimum value of β, which is $\pi - \alpha$, as u plus an allowance for deionization of the control grids.

(4.2.3) Firing Circuit.[9]

In practice, a d.c. bias is used to hold the control grids negative and a pulse of the same frequency as that of the main anode voltage, and of sufficient magnitude to overcome the bias and to permit the main anodes to fire, is superimposed on it. For this equipment the firing pulses are derived from peaking units comprising a transformer with a Mumetal core and a series reactor. The reactor serves to produce a triangular current waveform 90° out of phase with the voltage, and the Mumetal core of the transformer is such that it saturates sharply, with the result that, except for a few degrees when the reactor current passes through zero, the transformer core is saturated and the transformer secondary voltage is as shown in Fig. 5.

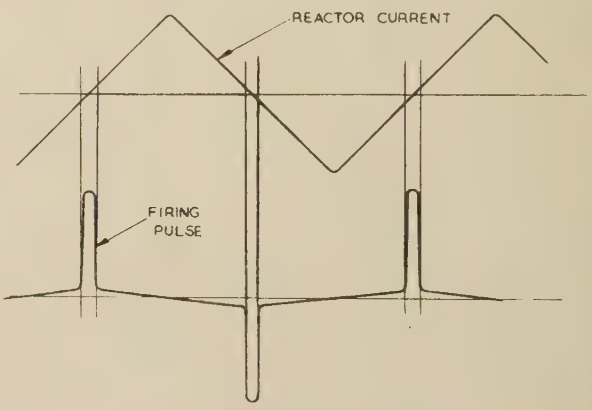

Fig. 5.—Peaker waveshapes.

The d.c. bias is of fixed potential and is obtained from a 3-phase bridge-connected selenium-iron rectifier, the output of which is partially smoothed by a capacitor. It is supplied from a small insulating transformer and is loaded on to a stabilizing resistor to prevent the sudden fall in bias potential which would otherwise occur when the main rectifier anodes fired.

(4.2.4) Phase-Shift Circuit.

To obtain the infinitely variable firing delay necessary, the firing-pulse circuit is supplied through a static phase-shifting circuit; this consists of a 6-phase diametric star-connected transformer across the phases of which are connected preset fixed resistors and saturable reactors as shown in Fig. 6(*a*). The supply to the peaking unit is taken from the star point of the transformer and the junction of the resistor and reactor on each phase. By varying the reactance of the saturable reactor the phase angle of the output varies as shown in Fig. 6(*b*).

(4.2.5) General.

When the main reversing contactors have been operated for inversion, an auxiliary contactor operates to retard the grid connections by 60° to give the extra range to the phase-shifter necessary for inversion. The switching of the grid circuits is

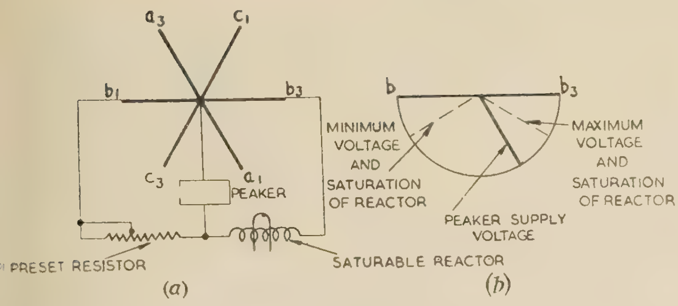

Fig. 6.—Static phase-shifter.

(*a*) Circuit.
(*b*) Vector diagram.

done on the primaries of the peaking transformers to avoid any break in the negative bias circuit. During the main contactor switching, therefore, arc suppression is applied to the rectifier.

The power required in the grid-control circuit is very small, the diametric star transformer in the phase-shift circuit being rated at 1·5 kVA. The control circuit requirements are also very small, a variation of 0–0·5 amp in the saturable-reactor control windings being sufficient to give full control of voltage from zero to maximum, rectifying or inverting.

Circuits have been developed which incorporate the pulse and bias functions in a single form, and there are others that incorporate the pulse and phase-shift functions in the same unit,[9] the choice of circuit depending on the manufacturer's preference and on the application.

(4.3) Rectifier Transformer

(4.3.1) Effect on Transformer Design.

The transformer for a rectifier/inverter scheme must be designed so that under the worst conditions of inverter operation the firing limits specified in Section 4.2.2 are never exceeded. These adverse conditions occur when peak loads (when u is greatest) coincide with a low supply voltage (when β is a minimum). This results in a transformer 10–20% larger than that necessary for the equivalent free-firing rectifier duty, and always involves operation during rectification with some firing delay.

The effect on the design of the Monk Bretton transformer is typical in this respect, the principal design figures being:

Nominal working full-load voltage	500 volts, d.c.
Design free-firing full-load voltage	580 volts, d.c.
Regulation at full load	41 volts
Arc drop	22 volts
Open-circuit voltage	643 volts, d.c.
Transformer reactance	8%
Supply reactance	1%

For peak inversion of twice full load with the supply voltage 15% low,

$$\cos\beta = \frac{500 - (2 \times 41 + 22)}{643 - 15\%} = 0{\cdot}72$$

and therefore $\beta = 44°$.

The effective reactance at twice full load with the supply voltage 15% low is 21·2%, and, from Fig. 7 of Reference 8, we get an overlap angle, u, of 23°, leaving a margin of 44° − 23° = 21° for deionization.

(4.3.2) Current Waveshapes.

With grid-controlled rectifiers and inverters it is apparent that the d.c. waveshapes are very distorted and that, as the direct voltage approaches zero, there will be a tendency for the current to become discontinuous. This distortion may possibly affect the commutation of the winder motor, and will almost certainly result in a slight increase in armature and winding temperatures. However, works tests made several years previously in connection with the more general application of grid-controlled-rectifier motor drives, and later confirmed independently,[12] indicate that with 6-phase, and over, operation trouble from this source is more theoretical than real. The use of d.c. reactors, as shown in Figs. 3 and 4, further reduces the possibility of trouble. These reactors smooth the ripple and thereby ease the duty on the winder motor. In the Monk Bretton application, the reactor was designed to ensure continuous current under all conditions of operation. It will be clear that, the lower the number of phases, the larger the reactor has to be to achieve this.

Because of the distorted direct load current, the rectifier draws a distorted current from the a.c. system, or, when inverting, injects a distorted current into the a.c. system. This distorted current comprises various harmonics[13] which are multiples of the fundamental frequency, as listed in Table 3.

Table 3

Harmonic Content of A.C. Waveform*

Order of harmonic	Percentage of harmonic		
	6-phase equipment	12-phase equipment	24-phase equipment
	%	%	%
5th	20	0	0
7th	14	0	0
11th	9	9	0
13th	7	7	0
17th	6	0	0
19th	5	0	0
23rd	4	4	4
25th	4	4	4

* These values are maximum and rather greater than will normally be obtained. Owing to phase unbalance, there may also be small amounts of lower-order harmonics present in the a.c. waveform of 12- and 24-phase equipments.

In passing through the various impedances of the a.c. supply system these harmonic currents cause voltage drops of the same frequency, which are, in turn, propagated throughout the entire a.c. network; if excessive, they may cause widespread interference. It is obvious that, the larger the rating of the rectifier, or inverter, in relation to the number of phases and the supply capacitance, the greater will be the risk of interference. The number of phases must therefore be assessed separately for each installation.

(4.3.3) Choice of Transformer Connections.

Because of the comparatively low rating of the Monk Bretton installation, it was decided that 6-phase operation was adequate and would not cause any undue interference. On this basis, the triple-star transformer connection was used, because it is the more stable connection for grid-control operation and therefore more suitable for inverter duty than the more conventional double-star connection. It has a slight disadvantage in that it results in larger anode currents and a reduced rating of the rectifier, neither of which is serious in this instance. Above about 300 kW a triple-star transformer would be larger and would cost more than a double-star transformer, and this would have to be taken into account with the other disadvantages for larger ratings.

(4.4) Rectifier Faults and Protection

(4.4.1) Arc-Starvation Surges.

All mercury-arc rectifiers have a maximum current rating for any particular temperature, above which the ion supply to the arc fails and the current is chopped: when this occurs high-voltage

surges are produced, owing to the inductance in the circuit. It is usual to operate well below these current values, but under certain operating conditions they may be exceeded. For example, when starting up after a week-end shut-down, a winder motor may require extra effort to move it, and if the rectifier is cold the grid control may be adversely affected, resulting in misfiring. This could easily result in an over-current sufficient to cause arc starvation.

Because of the risk of damage from such surges, it is standard practice to fit some form of surge protection on all mercury-arc rectifiers. This normally takes the form of non-linear-resistance or spark-gap surge arresters connected between the anode and neutral or the anode and earth across all secondary phases. It should be noted that these surge arresters are designed, not to eliminate surges, but to limit their value to within the surge strength of the equipment. Elimination of arc-starvation surges is possible only by strict adherence to the manufacturer's instructions regarding methods and conditions of operation.

(4.4.2) **Over-Voltages due to Switching and Regeneration.**

With a drive of this nature there is also the possibility of over-voltages caused by a sudden demand for regeneration facilities when motoring, or when switching from motoring to generating or the reverse. As mentioned in Section 4, the equipment at Monk Bretton was provided with an ignitron loading unit, as used on traction systems, which therefore ensures that it is adequately protected from over-voltages of this nature. However, this method is too expensive to perpetuate on any new inverter scheme, and it is possible that a small fixed load in the form of a resistor connected across the motor would suffice to eliminate any sudden over-voltages due to regeneration. Such a unit would be relatively inexpensive to install and would consume very little power.

(4.4.3) **Over-Currents due to Backfires and Grid-Blocking Failure.**

Besides the normal insulation failure faults, mercury-arc rectifiers are liable under certain circumstances to backfires and failure of the grid blocking. For example, such faults could occur during surges caused by arc starvation or during overloads. A backfire is an a.c. short-circuit inside the rectifier vessel itself from one anode to another. If at the time of the backfire the rectifier is connected to a load which can feed back, there will also be a d.c. short-circuit via the rectifier cathode and the faulty anode.

Failure of the grid blocking when rectifying results in the voltage suddenly changing from its reduced controlled level to the full free-firing level, and, depending on the amount of firing delay, may be equivalent to a short-circuit on the d.c. system. Such a failure during inversion could be more severe, in that the rectifier and machine would be in series and the resulting short-circuit would be at double the normal voltage.

As with all other electrical equipment, there is a fault level and a duration of fault which the equipment can withstand, and any protection has to be designed with this in mind. In this connection it should be appreciated that a backfire produces fault currents in the transformer windings and rectifier vessel of 30–50 times normal. On the d.c. side it is usual to fit a circuit-breaker capable of interrupting any possible fault current due to short-circuit or failure of grid blocking in sufficient time to prevent the fault turning into a backfire. In the case of backfires, both the a.c. and the d.c. protection must function rapidly enough to protect the transformer and to prevent any undue gassing in the rectifier, which would cause permanent damage.

(4.4.4) **Temperature Control.**

In order to minimize the incidence of arc-starvation surges it is desirable to accommodate mercury-arc rectifiers in an ambient temperature controlled above a minimum value of 15–20° C; if this is not possible, temperature control of the rectifier has to be provided. The method of temperature control will vary with different makes of rectifier, and since it was necessary at Monk Bretton, anode and cathode heaters were provided and controlled by a common switch. In addition, thermostatic control of the cathode heater is provided, operated from the rectifier cooling-air temperature, while the rectifier cooling fan is controlled independently according to the rectifier temperature by means of a thermostat situated on the anode plate.

Protection against fan failure normally takes the form of single-phasing or thermal over-current protection on the fan motor. Occasionally, depending on the rating of the equipment and the duty, it may be possible to put a thermostat on the rectifier tank, but this is normally not practicable owing to the slowness of response of available thermostats.

(4.4.5) **Ventilation.**

With a small equipment such as the one at Monk Bretton, overall substation ventilation presents no problems. This would not necessarily be so with a larger equipment with increased losses to dissipate, and careful consideration has to be given to this problem in such cases. Excessive operating temperatures may result in backfires if not in more permanent damage to the equipment, so that measures should be taken to dissipate the heat generated in the rectifier equipment. The normal maximum cooling-air temperature for mercury-arc rectifiers is 30° C,[14] although they can be provided for operation up to 45° C by suitable derating.

(5) CLOSED-LOOP CONTROL

Of the three systems available for electrical winders the Ward Leonard drive with its inherent transition from power to braking is the most suitable for closed-loop control, and all the requirements listed in Section 2.4 can be readily met with it. However, economic considerations have led to considerable effort being applied to the development of control schemes for a.c. winders. It is impossible to meet all the requirements on this type of drive, although several systems have been developed which fulfil the requirements to greater or lesser degree.

The rectifier winder, although it requires selection for power or inversion, has a continuous availability of torque which gives it certain advantages over the a.c. winder from the control aspect. Furthermore, the inherent speed regulation is comparable with that of a Ward Leonard set and the control system is considerably more linear and less complex than that of the a.c. winder.

(5.1) Control System

The control scheme is shown in Fig. 7. It consists of three main control loops, namely speed control, current limit, and acceleration or retardation limit. In the speed-control loop, a reference voltage selected by the driver's lever is compared with a signal voltage derived from a tachometer-generator which is proportional to the motor speed, and the difference, or error, voltage is fed into a pre-amplifier. In the current-limit loop a preset reference voltage is compared with a current signal derived from a d.c. current-transformer and the error voltage is fed into a second pre-amplifier. Similarly, in the acceleration loop, a preset reference is compared with an acceleration signal obtained by measuring the rate of change of the armature voltage and the error is fed to a third pre-amplifier. The combined pre-amplifier output is amplified and used to control the static phase-shifter, producing an armature voltage proportional to the error. In each of the three main loops, subsidiary loops are connected for stabilizing the controls.

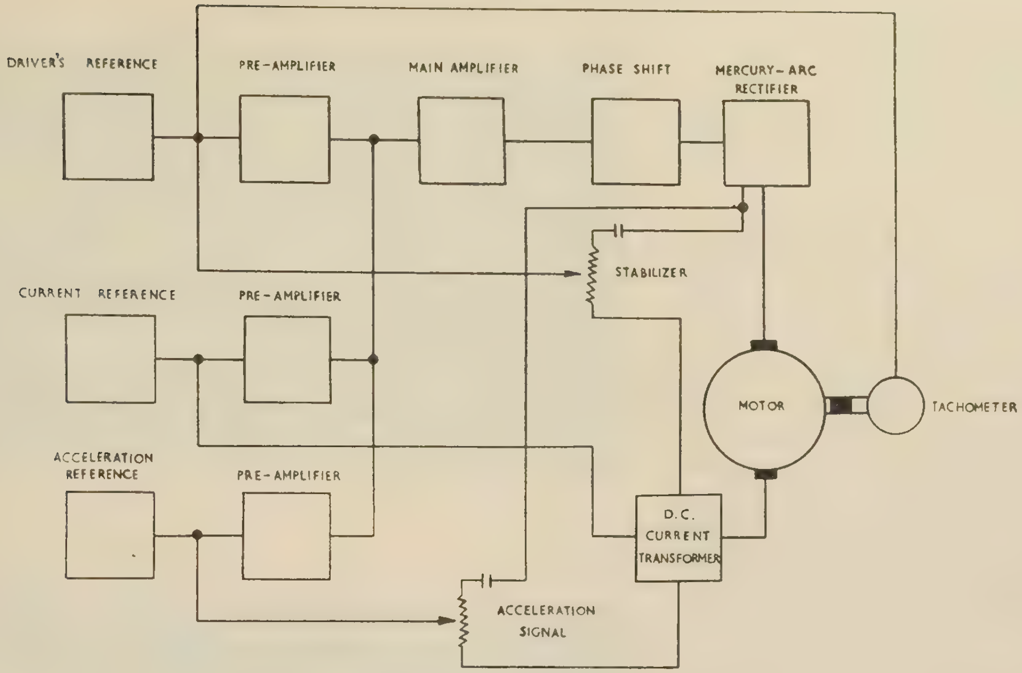

Fig. 7.—Block schematic of the Monk Bretton installation.

(5.2) Amplifier

(5.2.1) Control Amplifier.

In this type of industrial application it is as important that the amplifier equipment should be absolutely reliable as that the performance should be up to standard. From this point of view, magnetic amplifiers, which have been installed since about 1948, have shown themselves exceedingly satisfactory, and this type of amplifier was chosen in preference to either electronic or rotary amplifiers for this application.

The pre-amplifier consists of three series transductors without self-excitation, the control windings being completely separate—an arrangement which is very convenient, since it avoids interaction of the separate controls. A further advantage of this system is that this type of transductor is relatively insensitive to ripple voltages which are present in large quantities on any grid-controlled-rectifier circuit. The three output windings are connected in series with an a.c. supply and a common load rectifier. In normal speed-control operation the current and acceleration transductors are presaturated by the reference voltages and exercise no control of the output. If, however, the limiting current or acceleration is reached, the appropriate transductor is desaturated and control is taken from the speed-control loop. The rectified output of the pre-amplifier then feeds a control winding of an auto-self-excited transductor, giving a d.c. output into the control windings of the phase-shift circuit.

(5.2.2) System Sensitivity.

If an error voltage V_e is required to produce maximum speed while raising full load, i.e. the reference exceeds the tachometer voltage by V_e volts when rectifying, and an error V_e' is required for full speed while lowering full load, i.e. the tachometer voltage exceeds the reference by V_e' on inversion, the speed for the same reference in the two conditions will differ by an amount corresponding to $V_e + V_e'$. This is an inherent feature of any one-sided system and can be eliminated only be reducing the reference voltage when the control changes from power to inversion. A similar effect is present in the a.c. winder, but not in the Ward Leonard system.

(5.2.3) Reverse-Error Relay.

As stated in Section 4.1.4, when a change is required from rectification to inversion, it is necessary to detect when the actual speed exceeds the required speed. When this condition occurs, the polarity of the error voltage changes sign, and the amplifier input has to be switched to accept errors of this reverse sign. In order to initiate this change-over, a reverse-error relay is used, consisting of a 2-stage magnetic amplifier whose output feeds a contactor. In order to prevent hunting of the contactor, the amplifier bias is switched to give a dead zone between the pick-up and drop-off.

(5.2.4) Acceleration Limit.

In the Monk Bretton installation a decrease in reference voltage operates the reverse-error relay and switches the control to inversion. If, however, the decleration limit could be exceeded by the natural retardation of the system, power would be required during the decelerating period. The present control is unable to provide this, since it can call only for zero electrical braking. This defect may be overcome by applying a limit to the rate at which the reference voltage changes when the driver's lever is moved. If the reference varied at a rate required to give correct deceleration, a comparison of speed and reference would enable the control to stay on power under these conditions. In normal coal-winding, where the reference is reduced by cams at the end of the wind, such a condition would obtain and the preset deceleration can thus always be achieved.

(5.3) Control-System Stability

Experience with similar, though smaller, controls indicated that a signal corresponding to the rate of change of armature voltage connected as a negative feedback would stabilize the speed-control loop, and in practice this proved to be correct. The current and acceleration limits were stabilized by feeding back the rate of change of amplifier output. An analytical justification of these conditions is given in Section 10.2, while the results show the practical realization.

(6) OPERATIONAL RESULTS

The Monk Bretton winder was not required to go into production for some time after the equipment was installed, and this enabled exhaustive tests to be carried out on the system, some of which are described below.

(6.1) Winder Operation

Tests carried out with different loads in either the ascending or descending cage and at various speeds have indicated that the accuracy of the speed control is of the order of $\frac{1}{2}\%$ of full speed. This means that, for a given speed reference, the difference in speed between empty conveyances and a full load ascending, i.e. when rectifying, is about $\frac{1}{2}\%$ of full speed. Similarly, the same degree of accuracy is obtained when inverting, this being quite adequate for winder duty. A discrepancy of the order of 4% of full speed occurs with empty conveyances between the rectifying and inverting conditions, the reason for this being given in Section 5.2.2. Although it is of no serious consequence with a manually operated winder, it is one of the features in which an improvement is possible for automatic winders.

The accuracy of the current limit achieved was about 10% from zero to full speed, and the acceleration limit had similar accuracy but against load changes.

(6.1.1) Full-Speed Running.

Oscillograms showing the winder performance during a full-speed wind are shown for a full load ascending in Fig. 8(*a*) and for a full load descending in Fig. 8(*b*). On both tests the control lever is thrown fully over at the point A whilst the winder brakes are still applied and the current limit comes into operation. At B the brakes are released and the acceleration limit becomes effective.

With the ascending load a heavy current is required to maintain the acceleration, this current being maintained until full speed is attained at C. The speed control operates during the constant-speed portion of the wind, power being drawn from the supply until, at D, the speed reference voltage is reduced to zero. At this point a change occurs from rectification to inversion, the interval for this change being clearly discernible between D and E. During this interval the load is retarded naturally by gravity, and when control is again exercised, very little inversion is required to maintain the retardation. At F the brakes are applied to stop the winder.

With the descending load very little power is required to maintain the acceleration, and full speed is attained at C. The descending load continues to accelerate the winder, and a change is required to inversion. This occurs during the interval C–D; at D, when the inversion contactors close, the tendency for the current to build up rapidly is clearly indicated. The closed-loop control brings the speed down to the required value, but an overshoot of the order of 2 ft/sec occurs during the change-over. The need to keep the duration of this change-over to a minimum is apparent. During the full-speed portion of the wind the speed is maintained constant while inversion is taking place. At E the speed reference voltage is reduced to zero, and the retardation limit comes into operation at a larger

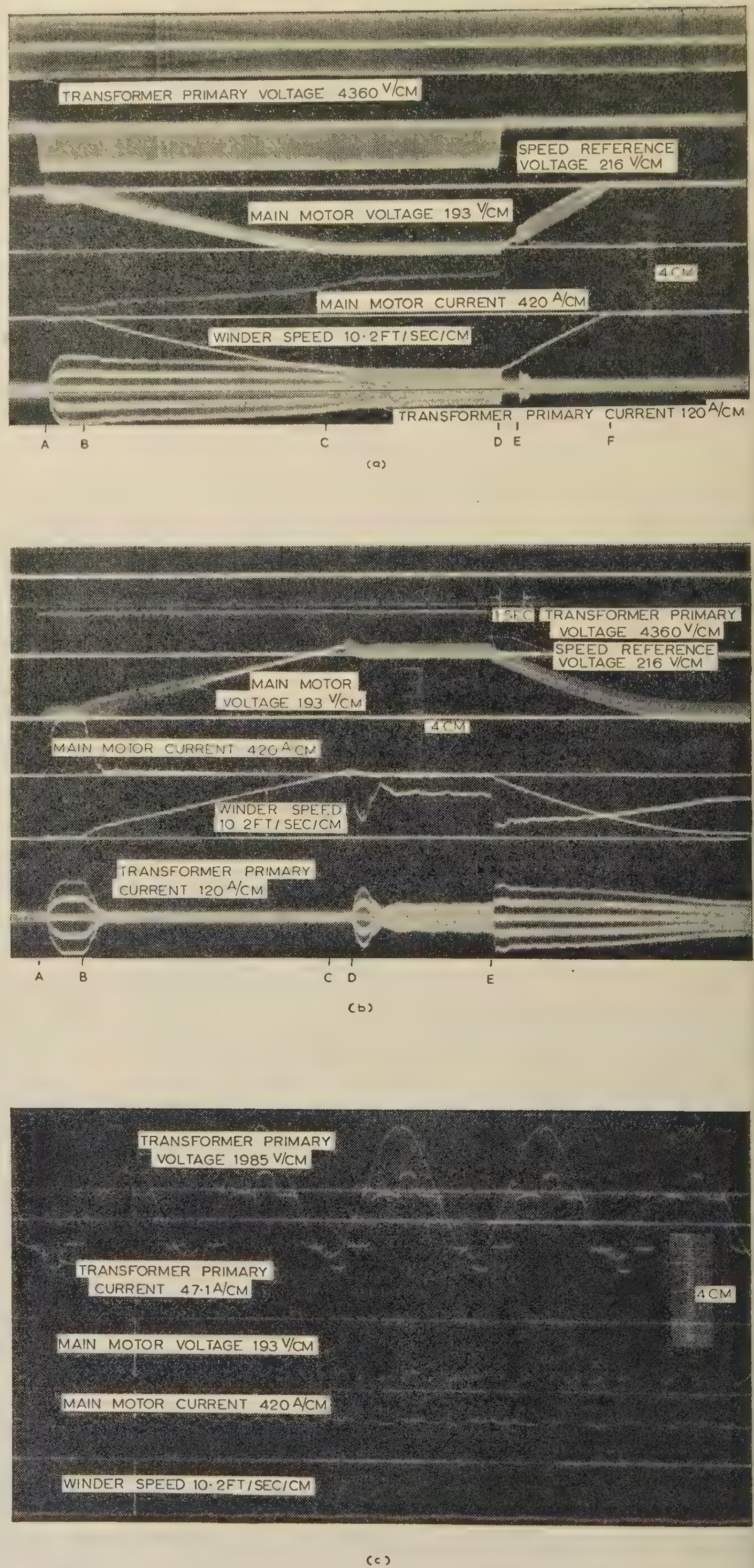

Fig. 8.—Winder performance at Monk Bretton No. 3 shaft with 2-ton load.

(*a*) Reverse wind, load ascending.
(*b*) Forward wind, load descending.
(*c*) Constant-speed reverse wind, load ascending.

current. The final stopping point of the winder is not shown on this record.

(6.1.2) **Reduced-Speed Running.**

Tests at various values of reduced-speed reference voltage show results similar to those discussed above, and it has been found possible to control the winder speed satisfactorily down to creep speeds of the order of 3 in/sec. If full-load torque is applied with the winder brakes on, when the brakes are released the speed attained is about 3 in/sec. These low speeds enable manoeuvring operation and shaft and rope examination to be carried out quite satisfactorily.

(6.2) Waveforms

Some of the waveforms on the above oscillograms are more clearly indicated in Fig. 8(*c*), which is a record taken during the full-speed portion of a wind with an ascending load, i.e. during the interval C–D in Fig. 8(*a*). Similar results are obtained with other load conditions.

(6.2.1) **Effect on Winder Motor.**

The motor-armature voltage waveform is typical of that obtained from a grid-controlled rectifier operating with firing delay; in this case the ripple is 6·8% of the mean voltage, but there is no evidence of this having harmful effects. Commutation under all load conditions is sparkless, and heating of the motor and armature is normal. None of the records taken, even at low speeds and low loads, indicates any discontinuity in the armature current.

(6.2.2) **Effect on Transformer.**

The transformer primary voltage and line current waveforms shown in Fig. 8(*c*) are typical of those obtained with grid-controlled mercury-arc rectifiers, and do not call for any special comments.

(6.3) Effect of Rectifier/Inverter on Associated Equipment

The effect of the operation of the rectifier/inverter on associated equipment has been mentioned previously, and some tests were carried out to investigate this.

(6.3.1) **Effect on Colliery Equipment.**

The rectifier transformer is connected through a circuit-breaker to the 3·3 kV busbars in the colliery substation. Also operating directly off these busbars is a 250 h.p. induction motor driving the mine ventilation fan, and a 10 kVA transformer for supplying the winder control equipment. Fig. 9 shows the waveform of the fan-motor line current and voltage, and the auxiliary-transformer secondary voltage for the following load conditions:

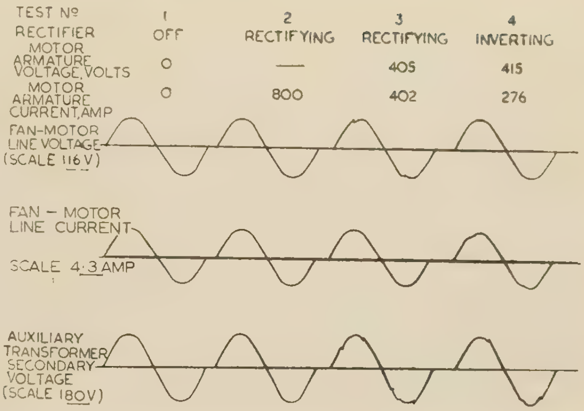

Fig. 9.—Effect of rectifier/inverter on associated equipment.

(*a*) Rectifier switched off.
(*b*) Rectifier on, motor stationary, current limit operating.
(*c*) Rectifier on, motor at full speed, load ascending, i.e. during rectification.
(*d*) Rectifier on, motor at full speed, load descending, i.e. during inversion.

It will be seen that there is very little change in these waveforms under the different conditions, and, in fact, no harmful effects have been reported on this equipment. It is therefore apparent that, so long as the winder forms only a small portion of the colliery load, the effect of the rectifier operation on the associated equipment can be ignored.

(6.3.2) **Effect on Supply System.**

The colliery 3·3 kV busbars are connected to 11 kV busbars through three 1 M V A 11/3·3 kV transformers. Also connected to these busbars are two 1 MVA, 11 kV/550-volt transformers supplying the colliery low-voltage board. The connection to these 11 kV busbars is brought in from the supply authority's system, and a harmonic analysis has been carried out on the voltage on these busbars for different operating conditions of the winder. The results of this analysis are shown in Table 4, from which it will be seen that the effect of the rectifier operation is negligible.

Table 4

HARMONIC ANALYSIS OF 11 kV SUPPLY VOLTAGE

	Test 1		Test 2		Test 3		Test 4		Test 5	
Winder speed, ft/sec	0		20		22		4		5	
Load	Nil		Full ascending		Full descending		Full ascending		Full descending	
Rectifier	Off		Rectifying		Inverting		Rectifying		Inverting	
Fundamental voltage, volts	10650		10650		10650		10650		10650	
Harmonic content	volts	%	volts	%	volts	%	volts	%	volts	%
5th	31	0·291	58	0·545	47	0·441	34	0·319	53	0·498
7th	11	0·103	16	0·150	8	0·075	15	0·141	12	0·113
11th	114	1·070	42	0·394	60	0·563	45	0·423	60	0·563
13th	24	0·225	13	0·122	5	0·047	3·3	0·031	12	0·113
17th	No trace		No trace		No trace		6·6	0·062	5·1	0·048
19th	No trace		No trace		No trace		0·6	0·006	0·6	0·006

(7) CONCLUSIONS

Theoretical considerations, confirmed by the Monk Bretton installation, suggest that advantages are to be gained by the use of mercury-arc rectifiers to control winder drives in increased efficiency, lower running costs, ease of installation and maintenance and accuracy of control. The harmonics from the rectifier should cause no interference with other colliery or other consumers' equipment, providing that due allowance is made for the rating of the equipment in relation to the supply rating when determining the number of phases to use for rectification and inversion.

It is doubtful whether the 'figure 8' connection will find much favour, because of its greater cost, and the limitation in contactor ratings make it probable that future trends will be towards the 'figure 0' connection using field reversal.

(8) ACKNOWLEDGMENT

The authors wish to express their appreciation to the National Coal Board, North Eastern Division, No. 5 Area, for the facilities granted to enable the tests to be carried out on the Monk Bretton installation, to Messrs. R. W. Worrall and W. Machin and their staff for assistance rendered during the course of this development, to Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the paper, and to their colleagues for the assistance given in its preparation.

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(10) APPENDICES

(10.1) Particulars of Monk Bretton No. 3 Shaft Winder

Power Supply.	
High voltage	3·3 kV, 3-phase, 50 c/s.
Low-voltage	220 volts, 3-phase, 50 c/s.
Duty.	
Shaft	Vertical.
Maximum winding depth	584 ft.
Net load per cage—men	3 840 lb.
stone	4 500 lb.
Maximum lowering load	4 500 lb.
Weight of tubs per cage	1 180 lb.
Number of tubs per cage	2
Weight of cage and attachments	8 000 lb.
Drum.	
Type	Single cylindrical.
Diameter	9 ft.
Width between flanges	4 ft 6 in.
Drum speed	45·9 r.p.m.
Winding speed	21·6 ft/sec.
Rope.	
Type	Flattened strand.
Diameter	1·25 in.
Winder Motor.	
R.M.S. rating	300 h.p.
Peak rating	600 h.p.
Speed	450 r.p.m.
Nominal armature voltage	500 volts.
Rectifier.	
Type	Pumpless steel tank.
Rating	195 kW.

(10.2) Analysis of Control-System Stability

By a combination of the measured frequency response of components of the system and by calculation of the outstanding details, the open-loop transfer function of the system was found to be

$$\frac{15}{(1 + 0{\cdot}4p)(1 + 0{\cdot}14p)(1 + 0{\cdot}29p)(1 + 0{\cdot}11p)}$$

This is plotted as curve (*a*) of Fig. 10, and shows that the system would be violently oscillatory at the loop gain corresponding to the required accuracy of the speed control.

The addition of a transient negative feedback from the arma-

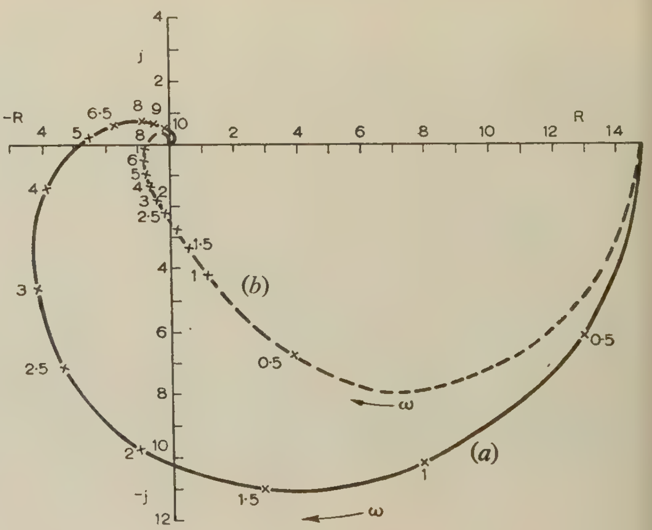

Fig. 10.—Open-loop response of winder to speed.
(*a*) Unstabilized.
(*b*) Stabilized.

ture voltage modifies the high-frequency response of the system and the transfer function may be approximated as

$$\frac{15}{(1+0\cdot4p)(1+0\cdot14p)(1+0\cdot1p)(1+0\cdot29p)+0\cdot5p(1+0\cdot29p)}$$

The feedback time-constant was chosen as 0·1 sec, derived from an RC network of 100 μF and 1 000 ohms.

The stabilized transfer function is plotted as curve (b) in Fig. 10, and shows that the system is now stable but apparently underdamped. In practice, the calculations proved to be pessimistic: the damping was better than the analysis predicted, owing probably to the non-linearities of the system and to a deliberate attempt to weight uncertainties in the analysis to give the worst result.

DISCUSSION ON THE ABOVE PAPER

Before the North-Western Centre *at* Manchester *5th March, the* Utilization Section *at* London *14th November, the* Sheffield Sub-Centre *at* Sheffield *20th November, and the* North-Eastern Centre *at* Newcastle upon Tyne *9th December*, 1957.

Dr. J. C. Read (*at Manchester*): I think the armature reversal is preferable to field reversal for this duty, provided that the armature circuit is reversed by a specially designed high-speed reversing switch rather than by ordinary industrial contactors. The switching duty is easy compared with that for which such special reversing switches are already being commonly used, so I feel that satisfactory and reliable operation of this item can undoubtedly be obtained. The paper shows that a shorter 'dead time' than at Monk Bretton will be needed in future, particularly for friction winders, to reduce the speed change during change-over and the subsequent surge of current and torque; this is where armature reversal is advantageous, and I do not think the authors are correct in claiming that field reversal will give better control of speed during change-over. Fig. A shows what must happen

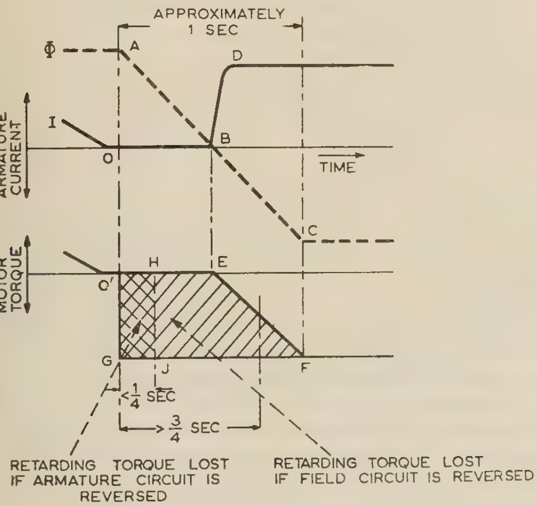

Fig. A

I = Armature current.
Φ = Motor flux.

during field reversal. At instant 0 the signal is given to change from rectification to inversion, and the motor flux is then reversed as quickly as possible, as shown by ABC. With a laminated field structure—which is quite expensive—this can be completed in about 1 sec, as the authors say. The ideal is for the armature current to remain at zero from 0 to B and then rise as quickly as possible to its full value, as shown at D. The torque produced, being proportional to the product of current and flux, is thus given by O'EF. The speed rise, owing to the lack of retarding torque during change-over, is proportional to the difference area between this and the ideal torque curve O'GF, i.e. to the shaded area O'EFGO'. The field reversal therefore produces an effect equal to a total interruption for at least ¾ sec. This is about the same as at Monk Bretton. However, the special armature reversing switches mentioned commonly give a total change-over time of 0·2–0·3 sec (area O'HJGO'), with a likelihood of reduction below 0·1 sec. Consequently, I think it is indisputable that armature reversal can give results superior to field reversal by a factor of 3 : 1 or more.

Mr. A. Gavrilovic (*at Manchester*): Both field and armature reversal systems should be made available to users. When very fast transition to braking is required, armature reversal must be used. It is claimed that field reversal results in gradual application of torque, but suitable controls can give the same effect with armature reversal. In fact, rectifier control can be as adequate as Ward Leonard control, apart from small reversal time.

Do the authors believe that 20% allowance on supply voltage for inverter operation is sufficient in general, or would they agree that each system should be investigated? What investigation and tests would they suggest?

What tests were carried out to determine the minimum deionizing time of the convertor? Additional safety would result, since the machine will normally deliver under 500 volts during regeneration.

There is no difficulty with double-star operation provided that the grid impulse width is adequate.

Would the authors comment on what provision should be made in large equipments, especially when using 12-phase transformers, to counteract the reduction of the available deionizing time in one 6-phase group due to commutation in other groups?

Since no demand for regeneration is made by field strengthening, what over-voltages do the authors fear and what is the difference in this respect from normal rectifier equipments?

From given ratings I deduce that the motor r.m.s. current is approximately 470 amp, whereas the convertor (presumably mean) current is 390 amp. The convertor transformer must be rated for the same r.m.s. current as the motor. Would the authors agree that it would be more straightforward and would conform with clauses 3.1 and 4.2 of B.S. 1698 to rate the whole equipment according to r.m.s. values?

Messrs. W. M. Brown and **N. Dudley** (*at Manchester*): We feel that the authors and their colleagues in other manufacturing firms have a great opportunity of extending rectifier control into the winder field, and that full economic analyses on individual cases will bring out strong advantages on this score as well as for the technical reasons the authors have advanced. However, a few words on the economic analysis might not be out of place, for the authors have not made the best use of the examples on which their Tables 1 and 2 are based. The authors appear to have compared rectifier drive with a.c. drive on the shallower shafts and smaller powers, and with conventional Ward Leonard drive on the deeper shafts and larger powers. While this distinction may be in line with certain established practice, it has more usually been found on economic grounds that the shallower and faster the wind the more the duty will favour conventional Ward Leonard control, and hence the more the duty will favour rectifier control in relation to either previous type. We are assuming that mechanical systems appropriate to the duty have

been assumed in each of the worked examples, so that effects of variables on this side could be neglected.

Power-consumption costs should be assessed, not only in terms of coal winding, but also taking account of men, stone and material winding, and intervening light-load losses. These losses have usually loaded the scales against conventional Ward Leonard control, but they can be greatly reduced if automatic-timed shut-down gear is fitted to the motor-generator control, and such a feature should be even simpler when applied to a rectifier. Due regard should also be given to the effect of electricity tariffs in relation to power-factor considerations.

In certain cases there may be some particular reason for using different maintenance or other costs for different types of drive, but these are not common, and the choice of drive on economic grounds usually rests on the relationship between the annual power-consumption costs and annual capital charges.

For the purpose of assessing depreciation charges, the expected life of the winder must be taken into account. In the particular circumstances these charges are best calculated on a 5% sinking-fund basis, so that if, for example, the expected life were 20 years, the annual contribution would be approximately 3·02%. Usually a much longer life is expected, but in order to be on the conservative side, we suggest that for the purposes of the sinking-fund calculation the period should be taken as 25 years, i.e. an annual contribution of approximately 2·1%. In all cases an additional 5% interest charge should be added. Thus the choice should fall on the scheme with the lowest total when the annual consumption cost is added to 7·1% of the capital investment. If two such totals are approximately the same, and the expected life is more than 25 years, the obvious choice will be the scheme with the lower consumption costs, but considerations of obsolescence, etc., make it unwise to extend the financial calculations beyond the 25-year period. In the great majority of cases the rectifier winder should show an appreciable financial advantage over either of the other types of drive, a further point in its favour being the capital saving in the building and foundation costs associated with motor-generator sets.

In Section 5.2.4 the authors mention some difficulty in coping with high-gravitational acceleration in their closed-loop system, and it would be interesting to know whether this problem has yet been solved. In connection with closed-loop control, they mentioned finding that the basic requirements could not be met by a.c. winders. Some further details of the shortcomings in this connection would be interesting.

On the question of ventilation it seems from the paper that fan cooling and temperature protection form essential parts of the rectifier operating equipment, and if this is the case we can see no real reason why such fan cooling should not also be employed on the main winder motor, with consequent economy in size and operating costs. Such considerations in relation to the winder motor cooling are not, of course, confined to rectifier drive.

Mr. T. H. Petch (*at Manchester*): I believe the limitation of 30% referred to in Section 3.1.2 is that imposed by a liquid controller. If metallic resistances are provided, we can and do use a figure of 15% for initial starting torque at standstill.

I agree that Tables 1 and 2 do not give full comparison, and feel that figures for Ward Leonard control should be added to Table 1 and those for a.c. drive to Table 2.

In Fig. 2 the variation of reactive power with time should have been shown. Also in the power-factor curve I believe a correction is required: the power factor should drop to near 0·1 at the end of the retardation period.

It is evident that the power factor during full-speed running on the rectifier winder is not better than about 0·77. This is because of the limitation of commutation on the rectifier when inverting, which means that not all of the full voltage available when rectifying can be used when inverting. It is also because of the desire to retain as nearly as possible the same maximum speed of the winder when lowering loads as when raising them. If it is desired to lower and raise at the same speed, the voltage for raising must be fundamentally the same as for lowering. Because the voltage for lowering under inversion is limited, that for raising must be limited to the same value. Hence we can only use about 77% of the full available voltage when rectifying.

If now we accept that we can use a larger motor, we can consider the use of field weakening, the motor being that much larger to ensure that the requisite torques can be obtained with the weaker field. With a weaker field we can run the motor at the same speed for reduced armature voltage. We can then consider running the motor when rectifying at full rectifier voltage, thus obtaining a much better power factor for this condition; when lowering under inversion we obtain the same maximum motor speed by running the motor at the reduced inversion voltage with a weaker field. However, in the outcome we have paid for a better power factor by investing in a larger motor.

Mr. W. Spence (*at Manchester*): In Fig. 8(*a*), where gravity is assisting retardation of the load, a linear retardation curve is shown, the winder coming to rest in about 4½ sec. In Fig. 8(*b*), where electrical braking is necessary, the main armature current is seen to rise to a value presumably limited by the retardation limit circuit, but it very soon falls away, and a long tail on the speed curve shows an excessive time to bring the winder to rest. Is the reason for this that there is insufficient gain in the associated control loop, and, if so, is this because there is difficulty in stabilizing with a higher gain?

Was the system simulated on an analogue computer before installation, and, if so, how did computer and site results compare?

What are the time-constants of the pre-amplifiers referred to in Section 5.2.1?

Could the authors amplify the phrase 'continuous availability of torque' in the context of the introduction to Section 5?

In Section 5.2.2 the reference to a.c. winders applies only to those employing a method of closed-loop control which operates with a steady-state error. There are closed-loop a.c. winders in service which operate with zero steady-state speed error, by the introduction of an integrator in the main control loop.

Dr. E. Friedlander (*at Manchester*): In Section 4.4.3 the authors refer to the need for a high-speed d.c. circuit-breaker for the protection of the transformer and the rectifier. This device is more important still for the protection of the winder in the case of an occasional commutation failure of the inverter, which, in my opinion, should be considered as inevitable. An inversion failure must occur if at the instant of regenerative motor braking from full speed a deep transient voltage dip happens to occur in the a.c. network. This, therefore, must not be considered as a misfunctioning of the equipment, but something depending on events outside the winder installation. However rare and improbable the coincidence may seem, one should accept its inevitability in the course of time. The high-speed circuit-breaker is in this case the first line of defence. If it fails the effect may be disastrous, because not only would the motor apply a heavy braking current, owing to the armature short-circuit, but the necessary tripping of the supply would at the same time cause the application of the mechanical brake. This coincidence could lead to a rate of deceleration greater than gravity, with all the consequences due to a transient slack rope on a drum winder. Rope slip of a friction winder would be a protective feature in this case, and could perhaps even be considered as a second line of defence. I wonder whether the authors have considered any additional

protection, particularly for drum winders, against this contingency.

In Section 4.3.2 the authors say that the rectifier draws a distorted current from the a.c. system and the inverter injects a distorted current. It should be made clear that the reversal of power does not apply to the distortion: the rectifier as well as the inverter acts as a frequency convertor delivering harmonic-frequency power into the system.

It is not clear why the authors have used a triangular reactor current in the peaky-wave transformer circuit if no use is being made of phase displacement by d.c. excitation in the transformer itself. Peaks are produced equally well during the zero passage of a sinusoidal current.

Mr. J. E. Peters (*at Manchester*): Two problems are likely to concern the supply authority in the application of rectifier winders, namely harmonic interference and voltage fluctuation.

The connection of large mercury-arc rectifiers to the system has caused interference troubles in the past, chiefly overloading of power-factor-correction capacitors and resonance troubles when the latter have been connected to the system through auto-transformers. Other troubles experienced include interference with ripple-control systems, induction-type instruments and protective relays, and noise in communication circuits, owing to unbalanced harmonic currents. Consultation between user, manufacturer and supply authority as soon as an installation is contemplated can avoid such troubles by agreement upon an adequate number of effective phases for any given ratio of rectifier load to system short-circuit power.

The second problem is that of periodical voltage fluctuation during the starting and accelerating period of the winder. It is known from practical experience that a 1 500 h.p. a.c. winder connected to a typical 2 × 10 MVA 33/11 kV supply substation produces a voltage fluctuation just under $1\frac{1}{2}\%$ at the 11 kV busbar, and it has been shown that this voltage fluctuation exceeds the borderline of irritation curve at four fluctuations a minute—a rate likely to be experienced in practice with starts for both winding and decking operations. From Fig. 2 it will be noted that approximately one-quarter of the way along the accelerating period the apparent-power demands of the a.c. winder and rectifier winder are equal, but whereas the former is operating at a power factor of 0·8, the latter is operating at a power factor of 0·3. We should therefore expect the rectifier winder to cause more serious voltage fluctuations than the equivalent a.c. winder, and I should like the authors' views on this point. This does not mean, however, that winders larger than 1 500 h.p. cannot be catered for, but it does mean that special precautions may have to be taken to segregate the colliery supplies from those to other consumers, resulting in greater capital cost in providing the supply.

Mr. R. W. Worrall (*at Manchester*): In view of certain questions which have been raised about the achieving of the theoretical aims in actual practice, as the using engineer I should like to testify to the extremely satisfactory performance and precision of control achieved on this pioneer installation at Monk Bretton. About 15 years ago, when on the manufacturing side of the electrical industry, I instigated and ardently advocated the development of the system described in the paper, as being the obvious manner in which to eliminate the disadvantages of the conventional Ward Leonard and a.c. winder systems, and it was therefore fitting that I should demonstrate my confidence by volunteering to be the 'guinea pig'. My preference in any future winding installations will be strongly for the rectifier system, except, of course, where the winding duty is of only an occasional and unimportant character which would not justify the additional capital cost above that of the comparatively crude a.c. system.

Mr. B. L. Metcalf (*at London*): Fig. 7 shows that there are three main control loops, for speed control, current limitation, and acceleration, respectively. If the acceleration loop were omitted the equipment would be simplified and the wind might be speeded up when light loads are being carried, thus utilizing the winder to its full capacity. Each control loop entails subsidiary stabilizing components, which all add to the first cost. What would be the result and the reduction in cost if the acceleration loop were omitted?

The authors are severe on the a.c. winder. The control gear is extensive, the liquid controller has limitations, power is wasted at reduced speeds, light load and light speed running is difficult, and neither regenerative nor reverse power braking are convenient. Little credit is taken for their work on dynamic braking. Finally, in Section 5 the authors state that, although considerable effort has been applied to the development of control schemes for a.c. winders, it is impossible to meet all the requirements listed in Section 2.4 for closed-loop control on this type of drive. Does this mean that we have gone too far in the refinements of control of the a.c. winder, making it too expensive and complicated? The paper gives insufficient information to enable a proper economic comparison to be made between the rectifier control and the a.c. drive, and more data would be welcome.

The effect of the poor power factor at starting increases the apparent power to be drawn from the line and makes the regulation worse than with both the Ward Leonard and the a.c. systems. How much worse it would be interesting to know. It will add to the cost of the supply lines and it may be necessary to bring in the supply at a higher voltage and step down for the winder. There may be some gain in the housing of the rectifier, as compared with the motor-generator set for the Ward Leonard winder.

In Section 4.1.3 the authors recommend the adoption of field reversing in order to be able to cope with the larger units, but I think at the sacrifice of speed of reversing. Is the reason that they cannot supply high-speed circuit-breakers for the larger ratings required? They propose considerable field forcing, involving alterations to the present methods of construction of d.c. motors. Do the authors propose to use rotary amplifiers? If so, what are the order of forcing required and the consequent size of the auxiliary motor-generator set, the increase in cost and the decrease in efficiency?

In Section 4.4.1 the authors state that 'elimination of arc-starvation surges is possible only by strict adherence to the manufacturer's instructions regarding methods and conditions of operation'. If plant like a winder will not work unless the manufacturer's instructions are strictly adhered to, it will fail in the long run.

What happens when we want to operate at peak loads at the beginning of a shift in mid-winter, when the winder has been standing over the weekend? What happens if we operate a tower-mounted winder by pushbutton from the bank? It is clear that very thorough measures are necessary to ensure that backfiring through sluggish response of the temperature control does not occur.

Mr. J. E. Boul (*at London*): I agree that field reversal appears likely to be preferred for winder duty, but consider that the grounds for this preference are much narrower than the authors have represented them to be. Section 4.1.2. gives 1 kA as a practical limit for armature reversal, because of limitations imposed by available contactors and the risk of switching surges. If full use is made of grid control to bring the current to zero before reversing the main connections, the duty on the contactor is reduced to that of a simple no-load polarity reversing switch, whereupon the problems of current interruption by contactor disappear and with them the risk of switching surges. Thus I do not agree that armature reversal need be limited to 1 kA.

Oscillograph records taken on what is believed to be the first

mercury-arc convertor built in this country for a reversing steel-mill showed a 'dead' time of 0·45 sec with a relatively slow armature reversing switch, which is about half the time deduced from an examination of Fig. 8. Faster times are considered quite practicable. For most winder duties a 'dead' time of 0·6 sec is probably acceptable, and in the interests of avoiding the mechanical maintenance of a heavy-current armature-reversing switch, field reversal appears to have a small advantage, especially now that laminated-frame machines are being produced at only a slight increase in cost over solid-frame machines.

Finally, I feel strongly that we should examine carefully our terminology on the subject of rectifiers for reversing drives before we become too deeply involved in a confusing jargon. The device commonly called the 'rectifier' must now serve the dual purpose of rectification and inversion. This problem is overcome by calling it the 'convertor' as defined in Document 84 of the International Electrotechnical Commission. Self-explanatory titles for the three possible circuit arrangements, namely cross-connected convertors, armature reversal and field reversal, are felt to be less confusing and rather more adequate than the phrases 'figure-8 connection' and 'figure-0 connection'.

Dr. W. G. Thompson (*at London*): Although the application of mercury-arc rectifiers to mine winders was discussed during the war, there was the experience of neither precision heavy-duty closed-loop control circuits nor mercury-arc rectifiers subject to frequent change-over to inversion. Information about the latter had to be drawn from the traction field, where figure-8 and figure-0 circuits had been tried for regeneration.

The principal difference between traction and mine applications is that in the former the rectifier is changed over to inversion indirectly and automatically in response to the driving on the train, but in mine-winding the control is applied via the regulator to the grid-control circuit of the rectifier. There have been many similar drives for large machines in industry, and it was realized that with the greater knowledge of closed-loop control gained during the war, together with these industrial applications, precision and reliability could be attained with rectifier/inverter drives.

In winder duty the full-load current may be required at low voltages, i.e. large angles of retardation of the rectifier grids. For successful operation under these conditions the rectifiers must have grids with strong screening action; they will, however, present a fairly large area of condensing surface to the arc path, thus tending to cause current chopping in the arc itself, as mentioned in the paper. The type of rectifier best suited to minimize these effects is one with separate side-arms or, alternatively, the single-anode type, because a good measure of temperature control can be attained at all vital parts of the rectifier—which minimizes the difficulties referred to by Mr. Metcalf.

For reversible drives the application of grid control provides the possibility of currentless operation of the change-over contactor, with consequent saving in maintenance, provided that advantage is taken of suitable mechanical design.

In some industrial applications the power factor can be improved by using field control over part of the reversing cycle. Has this any advantage in the present case?

Mr. I. A. Ferguson (*at London*): A supply system from which it is satisfactory to operate an a.c. winder may not necessarily be satisfactory for a rectifier winder, although the chances are that it will. A system which is unsuitable for an a.c. winder will invariably be unsuitable for grid-controlled rectifiers, but may be suitable for Ward Leonard drives. Consequently, when assessing the economics, any increase in supply capacity required to counteract adverse regulation difficulties caused by the introduction of grid-controlled rectifiers must be added to the cost of the rectifier plant.

As often as not the overall power factor of the mine system is worsened by the introduction of rectifier drives. Only at those mines where power-factor improvement is carried out by using synchronous machines for continuous-running plant, such as fans, compressors, etc., does the rectifier winder begin to hold its own against the a.c. winder or the induction-motor-driven Ward Leonard winder.

There appears to be no limit to the size of winders controlled by rectifiers. The best use of a rectifier tank capacity is obtained if the voltage of the d.c. motor is made as high as possible.

The rectifier winder with closed-loop control offers many advantages over the a.c. winder, provided that the supply system is suitable; and generally for the larger systems and new mines this will be so. Since the loadings to be hoisted to-day generally necessitate multi-rope friction winders, the technique demands speed and torque control, and acceleration limit if necessary, all of which are easily achieved by grid control.

However, the problem mainly hinges on the supply system: the more rectifier winders there are installed on any one system, the more difficult it may be to add others to it; nevertheless, there is a good future for the rectifier winder.

Dr. E. Friedlander (*at London*): The narrow limits of control accuracy claimed by the authors to be essential for a good winder control are not acceptable as an absolute rule. There are serious objections from the aspect of optimum requirements for manual control. The main advantage refers to easy decking by single-position contacts operating the brakes at a fixed point in the shaft. The application of the brake impulse timer,* the first model of which is in successful operation, should avoid the disadvantages of exaggerated precision.

The supervision of acceleration limits is unjustified. It is inadvisable to use this method to supervise the brakes, and possibly to counteract their action by a delicate electrical control, while acceleration control is not wanted for supervising the slip limits of friction winders. If the slip limit is plotted once as permissible acceleration and once as permissible torque as a function of a varying out-of-balance load, the diagram† shows clearly the superiority of torque limitation—which varies little—over acceleration limitation—which varies steeply. The proposed close control of deceleration is not justified by its advantages: if the average deceleration is correct, the winding time it can save becomes negligible. A constant error of 20% on a deceleration time of 10 sec will not waste more than 1 sec.

An advantage of armature reversal should be faster action. This applies particularly also to the initial starting delay, because the field of the motor must be de-energized at standstill. Moreover, the delay should be compared with the time the torque actually wanted is not available in either case, and not by the time of interruption of the circuit.

Mr. H. Kemp (*at London*): A rectifier winder will affect the supply system by injecting harmonic currents into it and by imposing on it large reactive current peaks during acceleration and so causing appreciable drops in the supply voltage.

The second effect, not mentioned by the authors, is the more serious of the two, and results from the rectifier voltage control being obtained at the expense of power factor, which falls to about 0·1 at the start. This means that when starting at twice full-load torque the winder will impose on the supply a reactive power peak almost equal to twice the rated power of the rectifier. The voltage drop produced in the resistances of the system by this reactive peak will be in phase with the system voltage, thereby directly reducing this voltage.

An important limit to the extent of voltage drops on a public supply system is the occurrence of objectionable lamp flicker. A

* *Proceedings I.E.E.*, 1953, 99, Part II, p. 609.
† *Mining Electrical and Mechanical Engineer*, 1957, 38, p. 167.

graph* gives the limiting values of periodic voltage fluctuations which can be tolerated for lamps without irritation to the human eye. For the range 20–80 fluctuations per hour, i.e. the range of duty-cycle frequencies of many winders, the maximum permissible voltage fluctuation is about 2%.

The rectifier winder must, therefore, be connected to the supply at a point (named by the C.E.A. as the point of common coupling, or p.c.c.) at which the system reactance referred to the rectifier rating, will not exceed 1%, i.e. at which the actual short-circuit capacity is at least 100 times the rectifier rating.

Considering now the limits to harmonic currents, the C.E.A. specifies† that for a 12-phase rectifier the short-circuit power at the p.c.c. should be 50 or more times the rectifier rating. Similarly, for a 6-phase rectifier the short-circuit power must be at least 200 times the rectifier rating.

It therefore follows from consideration of both effects that for a rectifier winder the p.c.c. must be determined from limits of harmonic distortion for a 6-phase rectifier, but from limits of voltage drop for a rectifier with 12 or more phases, which also means that the use of more than 12 phases offers little advantage to rectifier winders.

Mr. C. D. Wilkinson (*at London*): I appreciate the advantages of the d.c. winder motor and hope that the comparative simplicity and anticipated lower cost of rectifier equipment will make possible a wider use of this class of machine. It must, however, be borne in mind that reliability is a cardinal requirement in a mine winder. Do the authors consider that rectifiers will be as reliable as the Ward Leonard motor-generator sets used hitherto?

A division of opinion has arisen on the relative merits of field and armature reversal, but it is hoped that this is an issue which the experts will quickly resolve. It is suggested that where field reversal is adopted the time necessary to re-establish field and torque will be about 0·5 sec. This can be an important factor where consecutive decking of multi-deck cages is involved, for the cumulative delays will lengthen the winding cycle. Where armature reversal is adopted the reversing switch does not normally break current, but, in fixing its rating, would it not be wise to assume that at some time it will break full-load armature current?

Is backfiring likely to be troublesome, and will it be necessary to introduce artificial reactance into the transformers to keep down the short-circuit apparent power in this event?

With tower-mounted winders we hope to house the rectifiers and transformers in the tower structure; they will thus be located immediately above the pit shaft, and it will therefore be necessary for the transformers to be filled with a non-flammable coolant. Will this introduce any difficulty?

Mr. W. R. E. Taylor (*at London*): One of the major difficulties when operating inverter equipments is the maintenance of the grid firing impulse under adverse conditions of a.c. supply, due perhaps to a lightning strike or some other voltage transient. Commutation will not occur at the correct instant, and the anode will carry on firing into the danger zone, causing the d.c. circuit-breaker to trip out on reverse current. It would seem that this might be an objection to employing rectifier/inverters on such drives in South Africa or similar areas with a high rate of severe lightning storms.

In association with the effects of power factor and harmonics on the a.c. supply, do the authors feel that any advantage would be obtained if the rectifier transformer were arranged to operate direct off the incoming h.v. supply, say at 11 or 33 kV, and that any improvement would be obtained by having alternative delta- and star-connected rectifier transformers, even though it could not be guaranteed, of course, that the operating periods of any equipments would coincide?

Will rectifier/inverter equipments be applied to smaller drives of this nature, i.e. lifts and cranes?

Dr. D. Harrison (*at Sheffield*): I wonder whether the authors have given sufficient emphasis to the necessity for reliable, easily controlled, electric braking for mine winders. While the comparisons of power consumption given in Tables 1 and 2 are informative, they could be misleading, and figures showing the comparison for some typical mines based on a 24-hour period would be more realistic. These would probably indicate that the a.c. winder is not nearly so inefficient as implied by Table 1, whereas the Ward Leonard winder is much more inefficient than shown in Table 2. However, the true efficiency of a winder is measured by the cost per ton of coal wound, and not merely by power consumption. Thus, the importance of regenerative braking lies not in any possible saving in power consumption, which is likely to be very small in any case, but in the precision of control attained thereby. This permits of fast winding with safety. Similarly, the value of closed-loop control does not lie in the possible saving of a few man-hours, but in the faster winding which can be attained, because it is possible to work up to the limits of speed and acceleration with safety.

The information given in Section 6.2, showing how little effect the rectifier has on the currents and voltages of associated equipment, is of great value. This kind of information has not been available before, because so few inverter installations have been used.

Mr. W. Spence (*at Newcastle upon Tyne*): Few would dispute the statement that the best system for a rectifier-controlled winder is one which uses either the cross-connection shown in Fig. 3(*a*) with multi-anode rectifiers or the reverse-parallel connection of single-anode rectifiers, the advantage of the latter being the ability to use a single transformer secondary for both sets of rectifiers. Nevertheless, both methods are expensive compared with those which allow a single rectifier or group of rectifiers to be used for rectification and inversion. Economic considerations force the system designer to turn to these latter methods, which may be divided into two main groups. One reverses the field current of the winder motor and by grid control of the armature-supply rectifier permits regeneration; the other reverses the armature connections between the winder motor and the rectifier to bring about regeneration, again in conjunction with grid control. The latter is used at Monk Bretton, although this installation should not be regarded as typical of the best that can be done with armature reversal.

During a recent visit to Germany I saw two 4-rope friction winders mounted in a tower, each with two 19-ton skips, regularly raising 27 000 tons of coal in 16 hours each day, by fully automatic control. The winders were supplied from multi-anode rectifiers and used a field-reversal scheme, with cross-connected rectifiers feeding the motor field. For other types of winder, notably manually-controlled ones with variable loads, the superiority of the armature-reversal scheme for manoeuvring is at once evident.

A men-and-materials winder with 2-deck cages at the same colliery was supplied from rectifiers with armature reversal. The driver claimed that its response was better than that of the open-loop Ward Leonard system which it had replaced.

The armature-reversal scheme will do a good job for *any* type of winder, and in the interests of not dissipating development effort over too wide a field, I therefore believe that concentration on this method for the present is more likely to bring satisfactory results to the user than any other policy.

* Kronenberg, A. A.: 'Voltage Dips and Flicker', *Transactions of the American I.E.E.*, 1956, 75, Part II, p. 345.
† 'Harmonic Distortion caused by Mercury Arc Rectifiers', Central Electricity Authority, Engineering Recommendations G.5/1.

Mr. C. A. Maer (*at Newcastle upon Tyne*): An examination of Table 1 suggests that the cases have been chosen to prejudice unduly the case of the a.c. motor, and several examples could be given. It may therefore well be that only cases 2 and 3 (those having the most advantageous efficiency comparison for the a.c. motor of 118% and 117%) remain for a fair comparison with the rectifier at 100%.

These points raise the general question of efficiency. While efficiency is always important, the question is how important they are to the National Coal Board when the difference is small, bearing in mind that other factors have also to be considered in deciding the most suitable scheme to use with each application.

Mr. R. A. Hammond (*at Newcastle upon Tyne*): The statement in the second paragraph of Section 4.3.2 appears to mean that undistorted, i.e. perfectly smoothed, direct current would result in undistorted, i.e. sinusoidal, alternating current. This is, of course, incorrect. In fact, the figures given in Table 3 are the textbook ones which assume perfect d.c. smoothing.

Comparison of tests Nos. 2 and 3 in Fig. 9 suggests that, while 400 amp at full voltage produces a notch in the line voltage, 800 amp at zero voltage does not. This is unexpected. In Fig. 8(*a*), the transformer primary voltage appears to have a notch under zero voltage and 800 amp, d.c. conditions.

The calculations in Section 4.3.1 appear not to allow for the fact that the percentage reactance is effectively increased when the a.c. supply voltage is reduced. Making allowance for this reduces the time for deionization and the safe operation of the convertor to only 5°.

Mr. H. Watson-Jones (*at Newcastle upon Tyne*): The first rectifier-controlled winder at Zollern, Germany, in 1946 was a prototype to replace the existing motor-generator set and thereby avoid the no-load standby losses of that machine; however, the standing periods were considerable, owing to the time taken to locate and rectify faults. Simplicity and reliability are therefore of paramount importance if interference with coal output is to be avoided. Considerable experience has since been gained on both winder and rolling-mill drives, although I gather that in this country the latter have been mainly continuous rolling mills rather than heavy reversing mills requiring rectifier inversion.

We have on order in the Durham Division two Ward Leonard multi-rope tower-type winders of 2 000 and 1 000 h.p. respectively, which will be rectifier controlled and will have the advantages claimed by the authors of higher efficiency, reduced weight and space required and reduction in the maintenance necessary for rotating machines. The rectifiers and transformers will be mounted in the tower, thus avoiding the high cost of d.c. cable connections to the winder motor and minimizing the voltage drop. An agreement has been reached with the North Eastern Electricity Board regarding the harmonics in the supply system which will enable a 12-phase rectifier to be employed, with correspondingly lower capital cost.

Apart from waveform distortion and possibly poorer power factor, particularly in shallow winding depths, the only other disadvantage of rectifier control is the protection required from internal short-circuits and loss of control during change-over from normal running to inversion.

In rectifier substations for traction, high-speed d.c. circuit-breakers are provided with rapid reclosing features for protection against transient faults and short-circuits. How is the winder control restored without loss of winding time following high-speed circuit-breaker trips, which, for failure to safety, must automatically initiate mechanical braking? Furthermore, has adequate attention been paid to fault indication to enable the average colliery engineering staff to locate faults quickly and to restore control without delay?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. L. Abram, J. P. McBreen and **J. Sherlock** (*in reply*): For brevity we will reply to the discussion by subject rather than deal with each speaker individually.

Comparison between rectifier, a.c. and Ward Leonard drives.—In the paper, consideration has been given to some of the main technical factors to be considered when a comparison is made between the different types of electric winder drive. A number of other factors have been mentioned in the discussion, the most important being the economic. There are, however, so many variables in this aspect that it was considered to be outside the scope of the paper. Depreciation and interest charges, cost of buildings, maintenance charges and electricity tariffs must all be taken into account. These factors can vary quite appreciably, and it is therefore considered advisable to assess each installation on its merits.

One aspect of the comparison which is dealt with in the paper is efficiency. The examples cited in Tables 1 and 2 were selected from a number of mine shafts where the installation of new electric winders was under consideration. In each case, the original intention had been to install an a.c. drive for those examples in Table 1 and a Ward Leonard drive for those in Table 2. The winding conditions may thus not have been ideal for the particular drive originally intended—nor were they specially so for rectifier drives. The Tables therefore indicate that for the examples encountered in practice the efficiency of of the rectifier drive is higher than that of the other two types.

The difficulty of relating these figures to the consumption over a 24-hour period arises from the difficulty of specifying a typical 24-hour duty cycle. However, the consumption figures are based on the assumption that the ideal winding cycle is being carried out continuously. Adherence to the ideal cycle is, in practice, far more difficult to achieve and maintain on an a.c. drive than on a rectifier drive, and deviation from the ideal results in greater power consumption per wind for the a.c. drive. Interruptions in the continuous winding duty would have little effect, since in the idle periods the light-load losses for these two types of drive are approximately the same. The figures shown in Table 1 are thus such as to show the a.c. drive consumption as favourably as possible. The figures in Table 2 also show the Ward Leonard consumption as favourably as possible, since interruptions in the winding duty result in greater losses for this drive than for the rectifier drive.

Automatic shut-down of the motor-generator set when the idle periods are long is possible at the expense of complication and extra capital cost and has been adopted only in isolated cases.

Field and armature reversal.—The opinion expressed in Section 4.1.3 that field reversal is preferable to armature reversal was specific to winder applications and compared the concepts using standard contactors. On the general application of rectifier drives the problem is not so simple, as many questioners have pointed out.

The best summary of the position is probably this:

(*a*) Where dead times of ½ sec are acceptable, as on winder drives, field reversal gives the best solution, since a completely static control system can be produced in which every component is capable of handling any duty likely to be imposed on it.

(*b*) Where dead times of 0·1 or 0·2 sec are required, as in reversing mills in the steel industry, the choice is between figure-8 connection and figure-0 connection with armature reversal. If the latter alternative is accepted, the reversing switch will be suitable only for

zero-current operation and the control circuits must have a high reliability factor to minimize the risk of the switch operating on load. In view of this possibility, the economics of the two systems must be carefully considered. There is no doubt, however, that the figure-8 connection is technically the best solution.

Power factor.—The power factor of the rectifier drive is of importance only in so far as it affects the voltage fluctuation, which is discussed elsewhere, and the apparent power drawn from the supply. The latter generally affects the winder running costs because of a charge in electricity tariffs based on maximum demand measured over a fixed time interval. Calculations carried out on a number of proposed installations indicate that the maximum demands for the a.c. and rectifier drives are of the same order, while both are appreciably greater than that for a Ward Leonard drive on which a synchronous driving motor can be used, employing a system of power-factor correction. Improvement in the power factor during the full-speed period of the cycle will have a small effect on the maximum demand, and it is not considered that the additional cost of the equipment, e.g. the larger motor as suggested in the discussion, is justified. Far more beneficial results would be achieved if the power factor could be improved when running at reduced speeds, for not only would the maximum demand be reduced appreciably, but the voltage fluctuation would also be reduced.

It should be noted that in Fig. 2 allowance is made in the calculations for the winder auxiliary load of 20 kVA at a power factor of 0·8. At the end of the retardation period this load combined with the small rectifier load at a power factor of about 0·1 gives the power factor shown.

Number of phases and peak loading on a.c. system.—In general, it is expected that the peak demand of the rectifier on the a.c. system will determine the supply to be used: the higher the peak demand, the greater the system capacity needed if annoyance to other users by supply-voltage fluctuations is to be avoided. Since the permissible rating of rectifier loading for a given number of phases increases with system capacity, it is expected that in satisfying the conditions for peak loading the supply will be of sufficient capacity to make operation at more than 12 phases unnecessary. It will be obvious from this that the supply for the larger winders will have to be taken from further back in the system and, consequently, may have to be of higher voltage than that normally used for Ward Leonard drives.

Deionizing time.—The deionizing time required will vary with the type of rectifier and transformer connection used and with the rectifier temperature and load current. Similarly, the allowance to be made for possible supply dip will depend on the supply and is usually stated by the user.

Backfiring and system reactance.—Both the blocking duty on the rectifier and the prospective fault current decrease with increase in transformer reactance. But increase in transformer reactance, in itself, increases the size of the transformer and necessitates a larger firing advance angle and thus increases the transformer rating and the demand on the system. A balance must therefore be reached between these conflicting requirements.

Backfiring is not likely to prove troublesome on installations in this country. If backfires do occur they will probably be due to some easily recognizable fault in the installation.

Temperature control.—The intention of Sections 4.4.1 and 4.4.4 is to emphasize the importance of temperature control to the rectifier. The only way to avoid trouble from backfiring and arc starvation due to low temperature is to give the rectifier the condition it likes, a minimum ambient and cooling air temperature of 15–20° C, or to fit heaters and fan control and to see that they are maintained.

Type of rectifier.—We do not agree that rectifiers with separate side-arms or single-anode rectifiers are inherently more suitable for this application. Thousands of rectifiers with the anodes in the main condensing zone are in service all over the world on all types of duty, from supplying rolling-mill motors to aluminium pot lines. They have not proved to be more prone to low-temperature troubles than multi-anode rectifiers with side-arms or than single-anode rectifiers.

Protection.—In general, a break-through fault due to commutation failure is no worse, and probably less severe, a fault than a short-circuit fault on the motor alone. Therefore, even allowing for the highly improbable coincidence of excessive supply-voltage dip, maximum peak load and d.c. circuit-breaker failure, as suggested in the discussion, the conditions are no worse than those generally accepted.

High-speed circuit-breakers with automatic reclosure are used in traction substations because of the high incidence of self-clearing faults encountered in traction d.c. systems. In winder applications, faults of any description should be rare and the protection is in the form of insurance to prevent damage to the equipment if, by chance, a fault should occur. Thus it would be economically wrong and add unnecessary complications to the controls to follow traction-substation practice on winder installations.

In the event of the d.c. circuit-breaker operating, the winder control circuits are arranged to initiate mechanical braking so that the winder is brought to rest. The loss of winding time is kept to a minimum, since the winder control circuits can be restored by merely closing the circuit-breaker and carrying out the winder resetting sequence.

Acceleration limit.—On a Ward Leonard system acceleration limits by auxiliary closed-loop control are a simple and cheap method of holding a desired winding cycle. On both the a.c. and rectifier winders, however, the best method is to produce a speed reference voltage which itself changes at the desired rate and to rely on this to determine the cycle. Despite suggestions to the contrary, we feel that some method of acceleration control independent of load is essential, particularly for man-winding.

Closed-loop control system.—Preliminary calculations on the closed-loop performance indicated that no special difficulty would be encountered in obtaining the desired performance and no recourse was made to analogue computers. In general, the major problem with rectifier drives is the need to eliminate ripple voltages from the stabilizing circuits without affecting the transient feedback voltages. This is usually achieved empirically rather than by computation. The amplifier circuits were conventional and not of particularly high performance by modern standards. As shown in Section 10.2, their time-constants were 0·14 sec for the pre-amplifiers and 0·29 sec for the main stage. Reliability was considered more vital than performance in the design.

It is true that, by introducing an integration into the system, zero steady error can be achieved, but the resultant transient response is too slow to give the desired performance.

The wide variation on the deceleration times shown in Fig. 8 was due to incorrect setting of the retardation-limit circuit. The acceleration times on the two records are quite similar, showing that adequate loop gain is available.

Rating of equipment.—We agree that the rectifier equipment and the winder motors should be rated according to their respective British Standards. These ratings, expressed as r.m.s. values are, however, not necessarily the same, because of the method of calculating the r.m.s. rating of the motor which allows for the reduced cooling effects when the motor is operating at speeds below its nominal full speed.

Economy in the physical size of the winder motor can be effected by forced ventilation of the machine. However, an entirely separate fan system is required, since, not only is it

advisable for each rectifier tank to be provided with its own fan, but these fans are also thermostatically controlled so as to operate only when the rectifier tank temperature is above a predetermined value. Thus, it is considered that a decision to employ forced ventilation for the winder motor should be made on its own merits.

General.—The use of non-inflammable filling in the rectifier transformer usually increases the cost slightly, but it presents no difficulty. In Section 4.3.2 it was not intended to imply that a perfectly smooth direct current would result in a sinusoidal alternating current. There is no special significance in the type of peaker and phase-shift circuit used, except that it is simple, readily understandable and—in association with the control equipment—gives the required result. The use of inverters for small drives such as cranes and lifts is practicable and more of an economic problem.

If the operating conditions are adhered to, we have no doubt that the rectifier equipment will be as reliable in service as the motor-generator sets used on Ward Leonard drives. This is borne out by the experience on the Monk Bretton winder, where the time taken to locate and rectify such faults as have occurred has been negligible. On this equipment, as on future installations, the tracing of faults is simplified by the provision of trip indication and metering of the amplifier circuits.

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EARTHING OF LOW- AND MEDIUM-VOLTAGE DISTRIBUTION SYSTEMS AND EQUIPMENT

By F. MATHER, Member.

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SUMMARY

The paper states briefly the reasons for earthing low- and medium-voltage distribution systems and equipment. Reference is made to various methods of earthing and to the main difficulties encountered in putting them into practice, particularly in rural areas.

The main objects are to describe the development of the system known as protective multiple earthing, to show the advantages of this system and to explain the reasons for its adoption on a wide scale in the rural zones served by the North Western Electricity Board.

The experience of the Board with the p.m.e. system from 1949 onwards is described.

(1) INTRODUCTION

(1.1) Earthing of Systems

In Great Britain it is normal practice to connect with earth a point of every l.v. or m.v. system employed for general supply, in accordance with Clause 4 of the Electricity Supply Regulations, 1937. The main reasons are as follow:

(*a*) To stabilize the voltage of the l.v. system with respect to earth.

(*b*) To permit the l.v. system protection to operate in case of fault between any phase of the l.v. system and earth.

(*c*) To permit the h.v. system protection to operate in case of fault between the h.v. and l.v. windings of the supply transformer.

(*d*) To ensure, in the case of an m.v. system, that the voltage between any phase and earth will not normally exceed the phase voltage of the system.

(1.2) Earthing of Equipment

It is desirable that exposed non-current-carrying metalwork of electrical installations, in and about buildings served by public supply, should be earthed in accordance with Section 4 of The Institution's Regulations for the Electrical Equipment of Buildings, unless the principle of double insulation is employed, as described in Clause 401(ii) of the Regulations. This permits the circuit protective devices to operate in case of contact between live conductors and frame, thereby minimizing the risk of shock or fire.

The earthing of non-current-carrying metalwork associated with supply cables and overhead lines is covered by the Electricity Supply Regulations, 1937, and the Overhead Line Regulations. Earthing clauses are included in Regulations relating to factories, cinemas, coal mines, metalliferous mines and quarries.

(1.3) Co-ordination of System and Equipment Earthing

Earthing of a distribution system and its associated equipment is the responsibility of the supply undertaking, which is, however, not legally responsible for the effective earthing of consumers' equipment. Nevertheless, it is evident (and is clearly indicated in Clauses 406, 409 and 410 of the Wiring Regulations) that co-ordination is essential when supply is taken from the general l.v. or m.v. supply mains. The need for such co-ordination has not always received sufficient attention in the past, and investigations into cases of electric shock have often revealed a dangerous state of affairs arising from totally inadequate earthing arrangements.

These circumstances led the North Western Electricity Board to pass a resolution in September, 1953, to the effect that they would in future provide means of earthing the installations of new consumers taking supply at low or medium voltage. Thus the consumer has only to ensure that his earth-continuity system is complete and is connected to an earthing block provided by the Board at the service position. The Board then completes the earthing arrangements using one of the methods described below.

(2) DIRECT EARTHING USING CABLE SHEATHS

Where the system consists entirely of underground metal-sheathed cables with plumbed joints, it is generally satisfactory to bond the transformer neutral point and all the consumers' earth-continuity conductors to the cable sheaths. There is then a metallic path for earth fault current in case of breakdown in a cable or in a consumer's equipment, and normally a fuse or circuit-breaker will operate to clear the fault from the system. There are limitations to this simple method, since the current which flows when an earth fault occurs near the remote end of a distributor may be insufficient to operate a fuse rated to suit the load on the distributor. Thus a relatively high voltage may be sustained on the frames of consumers' apparatus connected to the cable sheath near the remote end of the distributor.

Connection of the frames to water pipes, either directly or through water heaters, has helped in the past, but with the increasing use of non-metallic water pipes, improved protective servings on cables and insulated joint boxes, the situation will need watching in the future. The probable use of plastic-insulated and sheathed distribution cables in the future will have a bearing on the matter, and there may be a wider application for protective multiple earthing than has previously been envisaged.

(3) DIRECT EARTHING USING OVERHEAD EARTH WIRES

There are three main objections to the general use of overhead earth wires in a zone supplied by overhead lines, the first two being the cost of the extra conductor and the difficulty of adding it to an existing line where clearance to ground or to Post Office lines is limited. The third objection is that a break in the earth wire would remain undetected and, when an earth fault occurred on a consumer's appliance, the potential of the frames of all consumers' appliances beyond the earth-wire break would be raised to the system phase voltage with respect to earth. In the past, the connection of consumers' earth-continuity systems to water pipes has eased the situation, but this may not apply in the future in view of the trend towards non-metallic water mains and service pipes.

(4) DIRECT EARTHING BY MEANS OF EARTH ELECTRODES

Direct earthing by means of an earth electrode at the supply transformer and electrodes at individual consumers' premises is

Mr. Mather is with the North Western Electricity Board.

seldom satisfactory. It is usually impracticable, or far too costly, for the consumers and the supply authority to provide electrodes of sufficiently low resistance to ensure that over-current protection will operate when earth faults occur. There must be many existing installations where direct earthing is totally unsatisfactory and should be changed to a better system. It is probably easier and cheaper to change to protective multiple earthing than to any other type of earthing in such cases.

(5) USE OF VOLTAGE-OPERATED EARTH-LEAKAGE CIRCUIT-BREAKERS

Voltage-operated earth-leakage circuit-breakers have a field of application because of their sensitivity and speed of operation, but the cost of the circuit-breaker with separate electrode and protected earthing lead is a disadvantage. A great deal of testing has been found necessary to ensure that circuit-breakers are in satisfactory working order, both at the time of installation and subsequently. Arrangements between consumers and the supply undertaking regarding the installation and maintenance of earth-leakage circuit-breakers have sometimes been difficult, and the fact that a minor fault may cause interruption of supply to the whole installation is a decided disadvantage. The reliability of such circuit-breakers has not been high, but there is reason to believe that recent designs will be better in this respect. Because of the factors mentioned, this method is not likely to be accepted as a general solution to the earthing problem.

(6) USE OF DIFFERENTIAL-CURRENT EARTH-LEAKAGE CIRCUIT-BREAKERS

Differential-current earth-leakage circuit-breakers have the advantages that they are not adversely affected by parallel earth paths through water heaters, etc., and can readily be used for the protection of individual circuits. They have, however, not yet been standardized, and it seems unlikely that they will be widely used except for industrial purposes, because of cost, size and lack of sensitivity.

(7) PROTECTIVE MULTIPLE EARTHING

The shortcomings of the methods of earthing to which reference has been made have directed attention towards protective multiple earthing (p.m.e.).

Fig. 1 shows how, by connecting each consumer's earth-continuity conductor to the service neutral ('neutralizing'), a

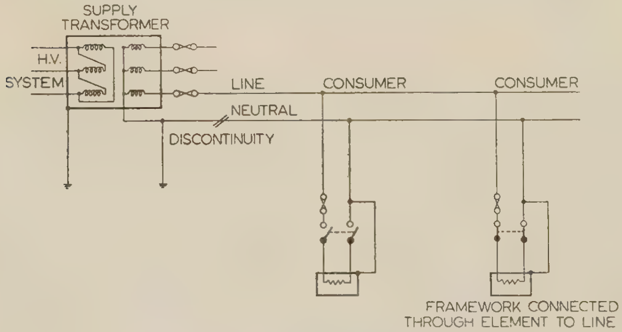

Fig. 1.—Neutralizing.

metallic return to the transformer neutral can be ensured for earth faults on the consumer's installation. This simple system would be ideal if there were no possibility of a break or bad contact in the neutral lines. In practice, however, this is liable to occur, and when it does the live line is connected, through the elements of any consuming appliances which may be in circuit,

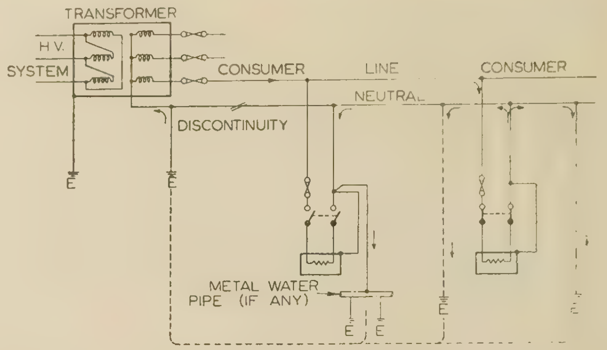

Fig. 2.—Protective multiple earthing.

to the appliance frames of all consumers on the side of the neutral break remote from the supply transformer. This dangerous condition is shown in Fig. 1.

Fig. 2 shows how, in the p.m.e. system, the neutral conductor is connected to earth at several points, so that if a break or faulty contact develops in the neutral conductor, there will still be a path for load current or fault current back to the neutral point of the supply transformer. The voltage appearing between consumers' appliance frames and earth will then be kept to a safe level.

This matter received the attention of the British Electrical and Allied Industries Research Association, and the results of a most comprehensive investigation by Dr. Taylor have been published.*

(8) ORIGINAL BRITISH REGULATIONS CONCERNING PROTECTIVE MULTIPLE EARTHING

The original Special Regulation and Approval to multiple earthing was produced by the Electricity Commissioners, with the concurrence of the Postmaster General, in 1940, following the investigation by the E.R.A. The following requirements were included:

(*a*) The total resistance to earth of the neutral conductor of each distributing main, with its branches and service lines, shall not exceed 2 ohms. If necessary to achieve this, additional earthing points shall be provided as equally spaced as possible along the neutral line.

(*b*) When the supply transformer feeds one distribution main only, a point at the transformer shall be connected to earth (the resistance of the electrode not exceeding 4 ohms) and shall be bonded to the metal sheath and armour, if any, of the electric lines concerned. This does not apply if the transformer supplies two or more distributing mains.

(*c*) At each supply transformer the earth electrode for the lower-voltage system shall be outside the resistance area of the earth electrode for metalwork associated with the h.v. system.

(*d*) A connection to earth (of resistance not exceeding 10 ohms) shall be made at the end of the neutral conductor of each distribution main and branch main.

(*e*) A connection from neutral to earth shall be made at the supply terminals of each consumer, except at premises where the service line is so arranged that (i) contact will take place between the phase and neutral conductors in the event of either breaking, or (ii) breakage of the neutral conductor will also involve breakage of the phase conductor.

(*f*) The neutral conductor shall be of the same material and cross-section as the phase conductor.

(*g*) Every connection with earth shall consist of a single electrode, not less than 6 ft long, driven as nearly vertically as possible into the general mass of earth, or a metal strip or wire of appropriate length laid in the earth. The connection to the rod, strip or wire shall be above ground and accessible for inspection.

(*h*) A fuse, circuit-breaker, link or s.p. switch shall not be

* TAYLOR, H. G.: 'The Use of Protective Multiple Earthing and Earth-Leakage Circuit-Breakers in Rural Areas', *Journal I.E.E.*, 1937, 81, p. 761, and 1941, 88, Part II, p. 415.

included in the neutral conductor of the supply system or consumer's installation.

(*i*) Non-current-carrying metalwork at the consumer's premises shall, where necessary to prevent danger, be bonded and connected to the neutral conductor at the service position.

(*j*) The resistance between any point on the consumer's earth-continuity system and its connection with the neutral conductor shall not exceed 0·5 ohm.

(*k*) If alterations are necessary to a consumer's installation, unless otherwise agreed with the consumer, the supply undertaking shall carry them out or pay the cost.

(9) COMMENTS ON ORIGINAL P.M.E. REGULATIONS

Despite the difficulties which supply undertakings were encountering with earthing in rural areas, little use could be made of p.m.e. under the above-mentioned Regulations for the following reasons:

(*a*) It was often impracticable to provide an earth electrode of not more than 4 ohms resistance at a supply transformer, because of rock or high-resistivity soil.

(*b*) It was frequently impracticable or very costly to provide an electrode of not more than 10 ohms resistance at the end of each main and branch.

(*c*) There were many cases, e.g. closely-grouped rural cottages in rocky terrain, where it was impracticable or too costly to provide a 6ft driven electrode or equivalent buried strip for each consumer.

(*d*) It was generally impracticable or too costly to reduce the overall resistance to earth of the neutral of each distributor to 2 ohms or less.

Because of these considerations, supply undertakings continued to provide overhead earth wires or to encourage consumers to install earth-leakage circuit-breakers or to leave the consumer to earth his equipment as best he could, since there are no statutory regulations which compel the supply undertaking and the consumer to take appropriate action to ensure safety in these circumstances. Nevertheless, some supply undertakings felt that they had a moral obligation, and were disturbed at the number of complaints of electric shock from the rural areas which, on investigation, proved to be due to inadequate earthing arrangements, either at the consumer's premises or at the supply transformer, or both.

(10) REVISION OF P.M.E. REGULATIONS

The E.R.A. continued to give consideration to the problems of earthing, particularly in rural areas, and devoted much attention to both economic and technical aspects. One result was the issue of E.R.A. Report Ref. V/T106 entitled 'The Cost and Efficiency of Protective Earthing of Low and Medium Voltage Systems by Various Methods', in which certain relaxations of the original p.m.e. regulations were recommended with a view to making them economically practicable. The report was published in a reduced form* in 1950.

(11) EXPERIENCE OF THE NORTH WESTERN ELECTRICITY BOARD WITH P.M.E.

The North Western Electricity Board, which had taken an active part in the E.R.A.'s work in preparing recommendations for the relaxation of the p.m.e. regulations, made application in January, 1949, to the Ministry of Fuel and Power for permission to apply them to two extensions in the rural area south-east of Macclesfield. Permission was granted in June, 1949, and the work proceeded forthwith.

In August, 1950, an extension of the approval was granted by the Ministry to cover the whole of the rural territory of the North Western Electricity Board within an area of 4830 square miles extending to the Scottish border in the north, Buxton and Cheshire in the south, the Pennines in the east and the Irish Sea in the west.

The main points of difference between the original and the relaxed p.m.e. regulations (as issued to the N.W.E.B.) are:

(*a*) It is no longer necessary to provide an earth electrode of resistance not exceeding 4 ohms at the transformer position. It is sufficient to ensure that the electrodes at, or near, the transformer are of such resistance that the fuses protecting the h.v. side of the transformer will operate should breakdown occur between windings.

(*b*) It is no longer necessary to provide a connection to earth not exceeding 10 ohms at the end of the neutral conductor of each distributing main and branch main. It is sufficient to ensure that the overall resistance of the neutral conductor to earth does not exceed $200/n$ ohms or 10 ohms, whichever is the lesser (n = number of consumers per phase).

(*c*) The substitution of the words 'near the end' for 'at the end', in respect of the earths on the distributor neutral lines and branch lines, gives a greater measure of flexibility.

(*d*) It is no longer necessary to provide an earth electrode at the premises of each consumer, although there is nothing to prevent this from being done when an electrode, such as a private water pipe, is available.

(*e*) It is permissible to use the metallic pipes of a water-supply system as a connection to earth as an alternative to a driven rod or buried strip. This rendered it possible to make use of private pipes from wells as electrodes which, connected to the neutral system, reduce its overall resistance to earth. Such pipes are often found in rural territory without public water supply and, since they make effective electrodes, they help to keep down the cost. Particulars of the private water pipes encountered in typical rural schemes are shown in Table 1.

Table 1

DETAILS OF TYPICAL CONSUMERS' PRIVATE WATER PIPES AVAILABLE AS EARTH ELECTRODES FOR P.M.E. SYSTEMS

Location	Soil resistivity	Details of water pipes*				Remarks
		Diameter	Length	Buried depth	Resistance to earth	
	kilohm-cm	in	yd	ft	ohms	
Cartchief Nook Farm	15·6	1	30	2	8·5	Pipe from private well to farmhouse
Slack Farm	15·7	1	12	~10	16·5	Pipe from private well to kitchen
Lower Dog Hill Farm	15·2	1	300	2	2·5	Pipe in very good condition. Laid in 1951
Nimble Nook Cottage	12·5	1	70	—	6·0	—
Newmarket Farm	14·7	1½	50	—	6	—

* All pipes are of galvanized iron.

The effect of the relaxed regulations has been to make p.m.e. a practical possibility, and it is now being used extensively for new overhead systems. It was found, however, that there were

* GOSLAND, L.: 'The Cost and Efficiency of Earthing at Low- and Medium-Voltage Overhead Line Systems', *Proceedings I.E.E.*, Paper No. 930 S, February, 1950 (97, Part II, p. 563).

certain factors which made it difficult to employ p.m.e. on existing systems where earthing conditions were known to be unsatisfactory and in need of revision.

The cost of altering consumers' installations from double-pole to single-pole fusing was considerable and, since neutral fuses are no more detrimental in a p.m.e. system than where direct earthing is employed, the Ministry of Fuel and Power were asked whether this requirement could be waived in respect of existing installations. This request was granted in September, 1954, subject to the consumer's earth-continuity conductor being connected to the incoming neutral conductor on the Board's lead-in side of the neutral service fuse.

There were many instances of relatively short overhead extensions from underground systems to premises where the earthing arrangements were unsatisfactory. Such cases could not be dealt with by using p.m.e. at the isolated premises only, since the regulations say, in effect, that p.m.e. must be used at all premises on the particular electrical system, or not at all. After an explanation of the circumstances to the Ministry, permission was granted for the use of p.m.e. on overhead extensions from an underground system, provided that the underground part of the system has a continuous metal sheath bonded to the system neutral earth connection at the transformer, and that the earth continuity conductors of installations connected to the underground part are bonded to the sheath of the service cable. With these relaxations the p.m.e. system is an effective and economical method of improving earthing conditions in many existing installations which cannot be dealt with in any other way at reasonable cost.

No reference is made in the p.m.e. regulations to street-lighting equipment, but it is the Board's practice to bond metal street-lamp brackets to the neutral conductor.

(12) LATER REVISIONS OF THE P.M.E. REGULATIONS

Since the date on which the Ministry gave approval to the North Western Electricity Board for the use of p.m.e. throughout their area of supply, certain other changes have been made in the regulations, which now appear as Appendix F of the 13th Edition of The Institution's Regulations for the Electrical Equipment of Buildings. The changes include the following:

(*a*) The overall resistance to earth of the neutral conductor of each distribution system shall not exceed 10 ohms, and shall be such that the fuses or automatic circuit-breakers protecting the high-voltage side of the supply transformer operate in the event of a breakdown between windings. There is no longer any reference to the number of consumers per phase, as in the earlier regulations.

(*b*) Unless there are two or more distributing mains from the transformer, there shall be a separate electrode at the transformer to connect the neutral point of the transformer to earth. This electrode must consist of a rod or tube driven into the ground, or a strip or wire laid in the ground.

(13) EXTENT OF P.M.E. INSTALLATIONS IN THE AREA OF THE NORTH WESTERN ELECTRICITY BOARD

Table 2 shows the extent to which the use of p.m.e. has grown between June, 1949, and December, 1956, in the area of supply of the North Western Electricity Board.

Table 2

Summary of P.M.E. Systems in the Area supplied by the North Western Electricity Board at December, 1956

	Sub-area						Area
	2	3	4	5	6	7	
Total number of single-phase p.m.e. schemes	14	17	268	344	140	298	1 081
Total number of 3-phase p.m.e. schemes	7	5	64	34	31	20	161
Total number of consumers connected to p.m.e. schemes	178	84	989	1 196	1 870	1 053	5 370
Minimum number of consumers connected to any one p.m.e. scheme	1	2	1	1	2	1	1
Maximum number of consumers connected to any one p.m.e. scheme	40	22	33	60	199	42	199
Maximum size of scheme (in terms of number of consumers) converted from other forms of earthing to p.m.e.	—	8	33	—	199	42	199

(14) COSTS ASSOCIATED WITH THE USE OF P.M.E. ON NEW AND EXISTING SYSTEMS

Sample checks have been taken on the cost of altering existing consumers' installations to comply with the p.m.e. regulations, and it has been found that the cost averages less than £5 per consumer. This includes the removal of neutral fuses in the consumers' installations, and since this is no longer necessary on account of the recent relaxation by the Ministry, the cost will be lower in future, because the only work now required is in connection with the consumer's earth-continuity conductor.

In one conversion scheme covering eight consumers and including three farms, the cost of alterations amounted to £11 15s. 0d. per consumer. This relatively high figure arose because a considerable amount of earth bonding was necessary at the farms, and because the consumers' neutral fuses were removed (prior to the relaxation being granted).

Apart from the work at consumers' premises (which applies only to the conversion of existing installations to p.m.e.) there is the cost of providing additional electrodes where necessary to comply with the regulations, and sample checks have shown this to be about £10 for a system with only one or two consumers, and £40 for a system with 10 consumers spread over two or three distributors.

(15) SPECIAL PRECAUTIONS TAKEN IN THE APPLICATION OF THE P.M.E. SYSTEM

Since it is important to maintain the integrity of distributor neutrals and—perhaps even more so—the neutral conductors of service lines, great attention is paid to these. Experience in the past has shown that conductor breakages are very infrequent, but there have been cases of faulty joints, particularly in the older existing systems where the line taps were not sufficiently resistant to corrosion. Line taps are now much more satisfactory, but, as a precaution, it is considered advisable to duplicate them on neutral jumpers and connections.

A standard method of making the earth connections to the neutral service line at consumers' premises has been adopted,

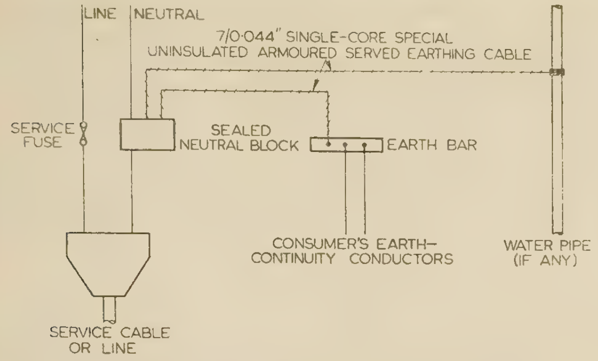

Fig. 3.—Connection at consumer's service position in p.m.e. system.

and is shown in Fig. 3. The consumer (or his contractor) is asked to bring the earth-continuity conductors of the installation to a small earth-bar provided by the Board at the service position. A 7/·044 in special single-core, armoured and served, uninsulated earthing lead is then taken from the earth block into the service neutral block, which is sealed. If there is a water pipe (e.g. a private metallic pipe from a well) which will function as an earth electrode, this also is connected by a similar type of earthing lead to the service neutral block.

With regard to the connections to earth electrodes other than consumers' water pipes throughout a p.m.e. scheme, there was some doubt about a clause in the p.m.e. regulations which states that connections to earth electrodes shall be made above the surface of the ground in a position where they can be inspected. It is well known that there can be danger to cattle, owing to the voltage gradient at the surface of the ground surrounding an earth electrode when current is passing, but this danger can be minimized by making the connection to the electrode, say, 2ft below ground, and bringing out a suitably insulated and protected conductor to a convenient point above ground level. Confirmation was obtained from the Ministry that such a method of connection is approved.

(16) SURVEY AND TESTING OF P.M.E. SYSTEMS

When supply to a group of rural premises is to be commenced by means of a high-voltage extension and a new l.v. or m.v. overhead system, consideration is always given to the use of p.m.e. A preliminary layout of the transformer, lines and services is prepared, and an example is shown in Fig. 4. Soil-resistivity tests are taken at the transformer position and near the ends of distributors and branches. Tests are taken on any water pipes which may exist at consumers' premises, to check their suitability as earth electrodes. Calculations are made to determine what types of electrode are necessary at the positions mentioned, and whether additional intermediate electrodes are needed to provide the requisite overall resistance between the neutral system and earth, and to ensure that, in case of fault between windings of the transformer, the h.v. protection will operate quickly. A typical data sheet is shown in Table 3.

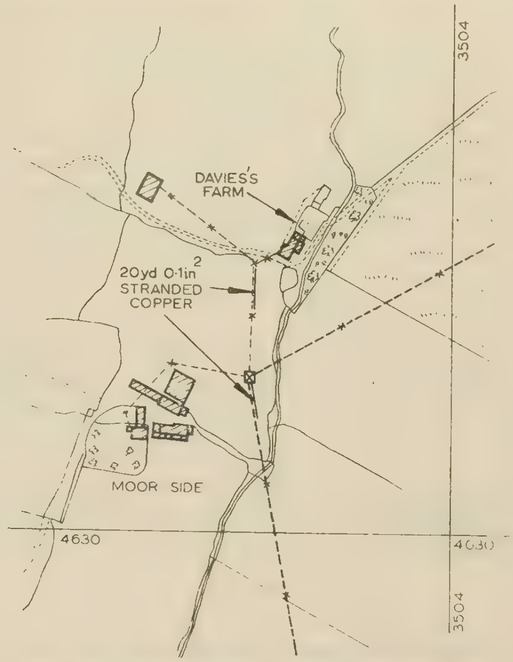

Fig. 4.—Proposed supply to Moor Side and Davies's Farm, Caton.
------ × ------ H.V. overhead line.
— — — × — — — L.V. overhead line.
⊠ Pole-mounted transformer.

If, in the light of the information obtained, it is considered that the use of p.m.e. will be practicable and economical (as it

Table 3

Data Sheet for P.M.E. System: Earth-Test Results for Moor Side and Davies's Farm, Caton

System	Position	Survey: Earth resistivity	Survey: Recommended earth electrode	Survey: Resistance to earth	Preliminary: Earth electrode installed	Preliminary: Resistance to earth	Amended: Earth electrode installed	Amended: Resistance to earth
		ohm-cm		ohms		ohms		ohms
H.V. metal-work	Single-member pole holding transformer	9200	20 yd $0\cdot1\,in^2$ stranded copper	8·0			20 yd $0\cdot1\,in^2$ stranded copper	7·5
L.V. and M.V.	First pole from transformer on l.v. distributor to Davies's Farm	9200	20 yd $0\cdot1\,in^2$ stranded copper	8·0			20 yd $0\cdot1\,in^2$ stranded copper	10·0
	Davies's Farm (house)				Private water supply system	4·0	Private water supply system	4·0
	Moor Side				Private water supply system	5·0	Private water supply system	5·0

H.V. fuses controlling transformer. Liquid type 14/30 amp operating at 108 amp in 0·1 sec. Combined neutral earth resistance: 2·5 ohms.

almost invariably is), the necessary working instructions are issued and the work proceeds. Contractors concerned with electrical installations in the premises are informed accordingly and are asked to conform with the p.m.e. regulations.

When the work has been carried out, tests are made as a check on the calculations and it is sometimes necessary to provide additional electrodes. All details are carefully recorded, as shown in Table 3, to facilitate comparison between the original test figures and those obtained in subsequent maintenance tests.

It is necessary under the regulations to give seven days' notice to the Post Office Area Telephone Manager that the system is to be brought into operation.

Certain tests to which reference has already been made must be carried out at each consumer's premises by the supply undertaking to ensure compliance with the p.m.e. Regulations.

The foregoing procedure refers to the application of p.m.e. to new systems, but similar steps are necessary when it is proposed to change the method of earthing of an existing system. In the latter case it is also necessary to determine what alterations must be made to existing consumers' installations and to reach agreement with the consumers concerned regarding the work involved.

(17) MAINTENANCE TESTS ON P.M.E. SYSTEMS

It was intended that, for a trial period at least, fairly frequent tests would be carried out on all p.m.e. systems to determine what degree of variation occurred in the overall resistance of the neutral to the general mass of earth. Shortage of suitable personnel has prevented this from being done in all cases, but the following information extracted from maintenance records shows the general position.

Table 4 shows the results of check tests on earth electrodes of typical p.m.e. systems after periods of 3–4 years. In a few cases there is appreciable change in resistance (which is being further investigated) but, in general, there is very little change from the original test figures.

In one Sub-area, all visible electrode connections are inspected at 2-yearly intervals and measurements are made of the resistance of electrodes associated with the framework of h.v. apparatus, and of the resistance to earth of the l.v. or m.v. system neutral. The results of these regular tests between 1950 and 1956 have not shown any significant variation from the original test figures.

In another Sub-area, check tests have been made on 17 single-phase and five 3-phase systems between 1950 and 1956. Here again, no significant change from the original test results has been observed, and there is little seasonal variation.

The general position, therefore, is that there is nothing in the experience over the last eight years to suggest that the efficiency of p.m.e. systems is liable to fall because of seasonal or other variations in the resistance of electrodes.

(18) EFFECT OF BREAKAGE OF DISTRIBUTOR OR SERVICE NEUTRAL

Not a single instance of an open-circuited distributor neutral or service neutral on a p.m.e. system has been recorded in the area of the North Western Electricity Board since the method was first used in 1949. This must, to some extent, be due to the special precautions taken to prevent such occurrences, as already described. Nevertheless, consideration has been given to the effects of open-circuited neutrals, and tests have been carried out to determine how the actual voltage between appliance frames and earth under such circumstances compares with calculated values. It was to be expected that actual measured voltages, at points where shock might be experienced, would be lower than those calculated, for two reasons: first, everything in the premises would tend to rise in voltage with respect to true earth and thus reduce the shock rise within the premises; secondly, with all metalwork in the premises bonded together, it is possible to experience shock only to objects like floors and walls, with which effective contact cannot be made unless they are damp.

The following Sections show the results of typical calculations and tests.

Table 4

Check Tests on Earth Electrodes of Typical P.M.E. Systems

Lowick Bridge				Lowick Green				Wood Broughton			
Consumers' electrodes		Board's electrodes		Consumers' electrodes		Board's electrodes		Consumers' electrodes		Board's electrodes	
1953	1957	1953	1957	1953	1957	1953	1957	1954	1957	1954	1957
ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms
4·0	4·0	4·5	10·0	9·0	10·0	12·0	7·0	4·0	3·0	6·0	5·0
4·0	4·0	3·0	3·0	4·0	3·0	8·5	10·0	4·0	3·0	5·0	5·5
1·7	4·0	3·0	4·0	4·0	4·0	1·0	2·0	3·0	3·0	4·0	5·0
1·5	2·0			5·0	4·0	7·5	9·0	3·0	3·0	4·5	5·0
2·0	8·0			4·0	3·0	7·0	7·0	1·5	2·5		
6·0	5·0			2·0	3·0	6·0	5·0	3·0	4·0		
				4·0	4·0	6·0	7·0	2·0	2·5		
				2·0	1·5	6·0	5·0	2·0	2·0		
				3·0	3·0	8·5	7·0	3·0	3·0		
				2·0	3·0						
				2·0	2·0						
				4·0	4·0						
				4·0	4·0						
				3·0	3·0						
				3·0	3·0						

(19) TESTS ON P.M.E. SYSTEMS

(19.1) Tests at Sandy Lane Cottages, Rawcliffe

This small system supplies two isolated rural consumers and a schematic drawing is shown in Fig. 5. Tests were carried out using a high-resistance voltmeter, to determine whether measured voltages at points where shock might be experienced under conditions of broken neutral and/or broken earthing conductors

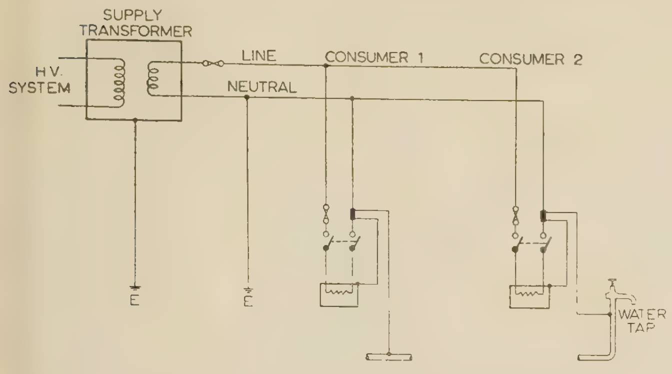

Fig. 5.—P.M.E. system at Sandy Lane Cottages, Rawcliffe.

agreed with calculated values. To avoid unnecessary risk to persons or cattle, the tests were carried out at the minimum voltage compatible with satisfactory instrument readings. For this purpose, a variable-ratio auto-transformer was introduced into the circuit adjacent to the supply transformer, as shown in Fig. 6.

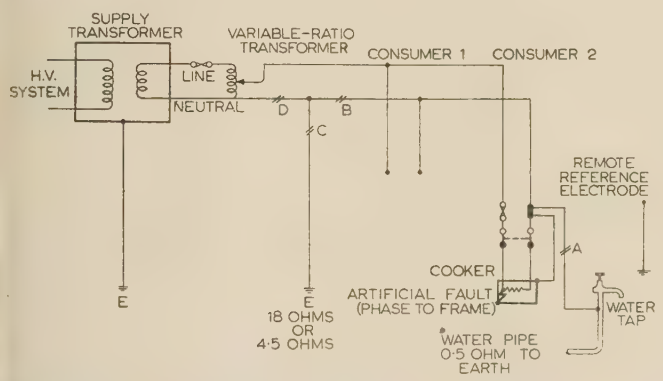

Fig. 6.—P.M.E. system at Sandy Lane Cottages rearranged for testing.
A, B, C and D are points where the conductors can be broken for tests.

The installation of consumer 1 was temporarily disconnected and observations were made in the premises of consumer 2. An artificial fault was applied between the phase line and the frame of the cooker in the latter premises. Table 5 shows the results, first at the test voltage and then increased proportionally to indicate figures that would have been obtained with normal voltage applied to the system, suitable allowance being made for regulation of the supply transformer. The reference earth electrode was 150 ft away from the nearest connection with earth so as to be outside the resistance area of the system.

The following points emerge from a study of Table 5:

(*a*) The figures for simultaneous breaks at A and B, compared with those for a break at B only, show the value of an earth electrode at each individual consumer's premises, since similar conditions would apply if a break occurred in the neutral of the consumer's service line. The present p.m.e. regulations do not require the provision of an electrode at each consumer's premises, but it is a wise precaution to provide one unless there is a metallic water pipe bonded to the general earth-continuity system which will serve the same purpose.

(*b*) A further point regarding the figures for simultaneous breaks at A and B is that the measured voltage between the cooker frame and points on the damp linoleum covering the floor approximates to the normal system voltage. The same voltage appears between the cooker frame and the water tap. It is therefore clear that in this instance there is no tendency for the potential of the building structure to rise with respect to true earth, and thereby minimize the shock risk inside the premises.

With a break at B only, however, the voltages between the cooker frame and the house floor and between the frame and tap are considerably less than that between the cooker frame and the remote reference electrode. This is apparently because the potential of the whole fabric of the building rises with respect to true earth, owing to the passage of current through the consumer's earth electrode. This appears to be a secondary beneficial effect of a local earth electrode at the premises.

(19.2) Tests at Cinder Hill

This system supplies seven scattered rural properties, either farms or cottages, as shown in Fig. 7. The same method of applying reduced voltage to the system as described in Section 19.1 was employed, although higher values were used than in the previous tests. The object in this instance was to determine, with the neutral conductor broken and various loads applied, the voltages that appear at points where shock might be experienced to the bonded metalwork.

At all consumers' premises were posted observers equipped with high-resistance voltmeters and radio sets for intercommunication purposes. Each observer also had a variable resistor, so that on receipt of instructions he could connect between phase and neutral a resistance of 60, 30 or 20 ohms, corresponding to a load of 1, 2 or 3 kW at normal supply voltage. During the tests, each observer applied the same load, so that voltage readings could be taken at loads of 1, 2 and 3 kW per consumer.

Table 6A shows the voltages measured at the stated test voltages and then proportionally increased to show figures that would have been obtained with normal voltage applied to the system. The first six tests were made with all the earths connected, giving an overall resistance of 1·5 ohms between neutral and earth. The remaining three tests were made with as many as possible of the

Table 5

P.M.E. System at Sandy Lane Cottages, Rawcliffe: Results of Tests under the conditions shown in Fig. 6

Point of conductor break	Earth resistance at C	Test voltage	Current input to system	P.D. between reference electrode and				P.D. between house floor and		P.D. between cooker frame and water tap
				Water tap	Cooker frame	House floor	Outside wall	Water tap	Cooker frame	
	ohms	volts	amp	volts	volts	volts	volts	volts	volts	volts
A	4·5	8·5 (180)	20 (400)	0	1·5 (31·8)	0	0	0	1·5 (31·8)	1·5 (31·8)
A	18·0	8·5 (180)	20 (400)	0	1·5 (31·8)	0	0	0	1·0 (21·2)	1·5 (31·8)
B	4·5	50 (235)	9 (40)	3 (14·1)	5·0 (23·5)	1·0 (4·7)	1·0 (4·7)	1·0 (4·7)	1·5 (7·0)	1·5 (7·0)
B	18·0	70 (238)	4 (13·5)	1 (3·4)	1·5 (5·1)	1·0 (3·4)	0	1·0 (3·4)	1·0 (3·4)	1·0 (3·4)
C	18·0	9 (180)	20 (400)	0	1·0 (20·0)	0	0	0	1·0 (20)	1·0 (20)
A and B	18·0	50 (240)	0	0	50 (240)	0	0	0	40–50 (190–240)	50 (240)

N.B.—Values given in parentheses are the measured results after adjustment for normal system voltage, with an allowance for transformer regulation.

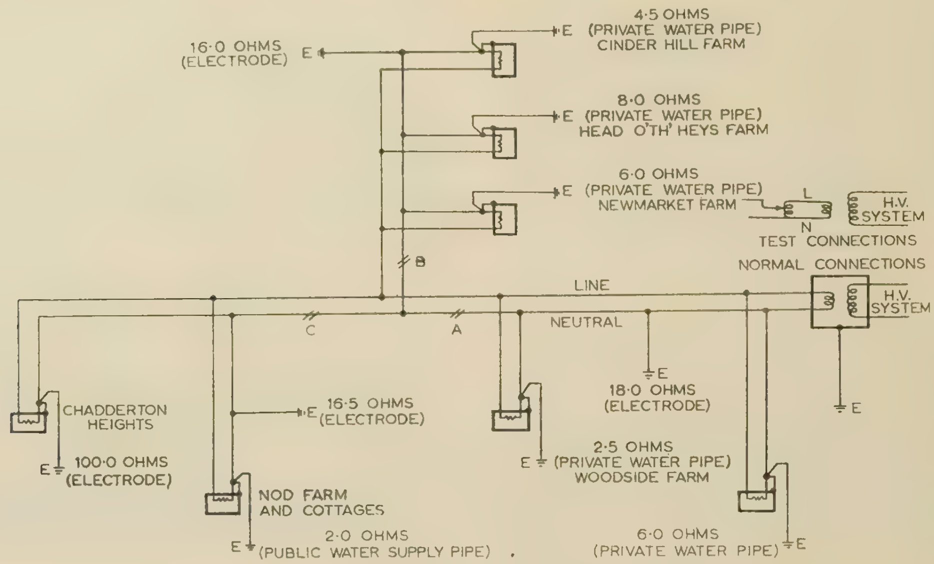

Fig. 7.—P.M.E. system at Cinder Hill.

Table 6A

RESULTS OF TESTS ON P.M.E. SYSTEM AT CINDER HILL (FIG. 7)

Test number	Point of neutral break	Load per consumer	Voltage applied to system	Woodside Farm		Head o' th' Heys Farm		Cinder Hill Farm	
				V_{fe}	V_{max}	V_{fe}	V_{max}	V_{fe}	V_{max}
		kW	volts	volts	volts	volts	volts	volts	volts
1	A	1	90 (238)	—	—	2·6 (6·9)	0·8 (2·1)	3·1 (8·2)	0·5 (1·3)
2	A	2	90 (236)	—	—	3·4 (8·9)	1·2 (3·2)	3·9 (10·2)	0·5 (1·3)
3	A	3	90 (235)	—	—	4·7 (12·3)	1·1 (2·9)	5·2 (13·6)	0·8 (2·1)
4	B	1	120 (238)	3·0 (6·0)	2·0 (4·0)	6·9 (13·8)	1·0 (2·0)	3·2 (6·4)	—
5	B	2	120 (236)	—	—	5·0 (9·8)	2·0 (3·9)	5·8 (11·4)	1·0 (2·0)
6	B	3	120 (235)	—	—	7·0 (13·7)	2·9 (5·7)	8·1 (15·9)	1·4 (2·7)
7	A	3	50 (235)	23 (108)	17 (80)	2·0 (9·4)	0·9 (4·2)	2·4 (11·3)	0·4 (1·9)
8	B	3	100 (235)	12 (28)	12 (28)	6·1 (14·3)	—	6·8 (16·0)	—
9	C	3	60 (235)	9 (35)	9 (35)	2·0 (7·8)	0·4 (1·6)	2·5 (9·8)	0·5 (2·0)

Table 6B

RESULTS OF TESTS ON P.M.E. SYSTEM AT CARTCHIEF NOOK (FIG. 8)

Test number	Point of neutral break	Load per consumer	Voltage applied to system	Cartchief Nook Farm			Slack Farm			Lower Dog Hill Farm		
				V_{calc}	V_{fe}	V_{max}	V_{calc}	V_{fe}	V_{max}	V_{calc}	V_{fe}	V_{max}
		kW	volts	volts	volts	volts	volts	volts	volts	volts	volts	volts
1	A	1	120 (240)	21 (42)	23 (46)	11 (22)	5 (10)	6·2 (12·4)	5 (10)	5 (10)	5·5 (11)	—
2	A	2	120 (240)	34 (68)	37 (74)	—	8 (16)	10·2 (20·4)	—	8 (16)	9·2 (18·4)	—
3	A	3	120 (240)	44 (88)	45 (90)	35 (70)	10 (20)	12·5 (25)	7 (14)	10 (20)	11·5 (23)	—
4	B	1	240	17	17	—	17	19	—	6	5	—
5	B	2	240	31	33	20	31	35	—	11	12	—
6	B	3	240	42	46	—	42	46	43	15	17	2

V_{calc} = Calculated voltage between appliance frames and earth.
V_{fe} = Measured voltage between appliance frames and reference earth electrode.
V_{max} = Highest voltage measurable between appliance frames and earth.

Values given in parentheses are the measured results after adjustment for normal system voltage, with an allowance for transformer regulation.

consumers' earths disconnected, but with the Board's electrodes connected, giving an overall resistance of 2·1 ohms between neutral and earth.

The following points are of interest:

(*a*) Since all metalwork in the vicinity of the electrical installations is thoroughly bonded, the only danger of shock is between the bonded metalwork and the floors, walls, etc. The observers therefore took numerous voltage measurements between the bonded metalwork and points such as stone floors, wood floors, composition floors, doorsteps, waste pipes and fireplaces. Metal plates were used to make contact with floors, and probes were used to reach into the joints of flagged floors and stone walls.

In Table 6A the highest recorded figures are shown, and the outstanding feature is that these figures are, in almost every case, much lower than the corresponding voltages measured to a remote reference electrode. This may be due partly to imperfect contact with floors, etc., and partly to the increase in potential of the whole fabric of the building with respect to true earth. It indicates that the actual shock risk is in many instances much lower than the calculated risk.

(*b*) While the last three tests were being carried out, a number of cows showed extreme reluctance to enter a yard in the vicinity of the earth electrode at Woodside Farm, although the voltage applied to the electrode did not exceed 23 volts. The electrode consisted of 25 yd of 1½ in-diameter metal pipe from a private source of water supply, the resistance to true earth being 2·5 ohms.

(*c*) The relatively high voltages recorded in the last three tests at Woodside Farm show the effect of having a low earth resistance at one side of a broken neutral and a much higher earth resistance at the other side. To avoid this as far as possible, on p.m.e. systems generally, it would seem advisable to concentrate any additional earth electrodes at the near and remote ends of a distributor rather than to distribute them evenly along its length.

(19.3) Tests at Cartchief Nook

This small system supplies three scattered farms, as shown in Fig. 8, and tests were made to find the effect of breaks in the neutral at A, B, C and D. A variable-ratio auto-transformer was employed, as in previous tests. With a break at A, a voltage of 120 volts was used and tests were taken with loads of 1, 2 and 3 kW per consumer. With a break at B, the full system voltage of 240 volts was used and tests were taken over a similar range of loads.

The results are shown in Table 6B and, for comparison, figures calculated from a knowledge of the various electrode resistances are also shown. The electrode resistances were determined by means of an earth-testing ohmmeter with hand-driven generator.

The main points of interest are as follow:

(*a*) The close agreement between the calculated voltages and the test results shows that on p.m.e. schemes the voltage distribution under broken-neutral conditions can be determined with sufficient accuracy without the need for comprehensive tests.

(*b*) The results of test No. 3 again show the undesirability of arranging the electrodes in such a way that the resistance to earth at one side of a break in the neutral conductor is appreciably different from that at the other side of the break. (See Section 19.2.)

(*c*) Tests were made at numerous points about the premises where shock might be experienced under broken-neutral conditions. The results are shown for comparison with the calculated and measured voltages between the bonded appliance frames and the reference electrode. In general, the shock voltages are about half those measured between the frames and true earth, because of the rise in potential of the fabric of the structure. Although this does not

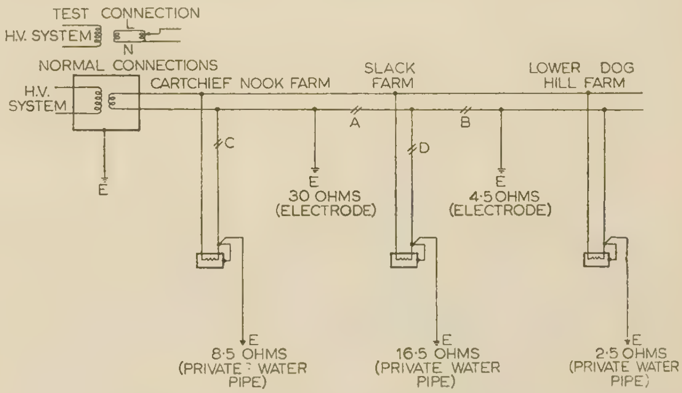

Fig. 8.—P.M.E. system at Cartchief Nook.

Table 7

Voltage Tests at Cartchief Nook Farm

Points to which measurements were taken from bonded appliance frames	*Voltage measured with 120 volts applied to system* volts
Floor near sink	18·0
Floor in front of cooker	8·0
Floor at coal place	10·0
Brass hob of fireplace	33·0
Flag floor in front of fireplace	33·0
Linoleum at front door	2·5
Wooden floor of bedroom	5·0
Flagged doorway to bedroom	35·0
Coconut matting in kitchen	5·0
Catch of wood framed door	3·0
Carpet in living room	2·0
Linoleum near bedroom door	28·0

N.B.—With 240 volts applied to the system, the voltages are exactly twice those recorded at 120 volts.
The voltage between the bonded appliance frames and the remote reference electrode is 90 volts.

Table 8

Tests with Broken Service Neutrals on the P.M.E. System at Cartchief Nook (Fig. 8)

Test serial number	Point of neutral break	Consumers' load	Voltage applied to system	Consumers' side of break		Supply side of break	
				V_{calc}	V_{fe}	V_{calc}	V_{fe}
		kW	volts	volts	volts	volts	volts
1	Cartchief Nook Farm (C)	1	90 (240)	11 (29)	12 (32)	1·8 (4·8)	—
2		2		19 (51)	19 (51)	3·2 (8·5)	—
3		3		26 (69)	25 (67)	4·2 (11·2)	—
4		6		38 (101)	—	6·3 (16·8)	—
5	Slack Farm (D)	1	60 (240)	13 (52)	16 (64)	1·0 (4·0)	1·0 (4·0)
6		2		21 (84)	25 (100)	1·6 (6·4)	1·0 (4·0)
7		3		26 (104)	29 (116)	2·0 (8·0)	1·8 (7·2)
8		6		35 (140)	—	2·8 (11·2)	—

V_{calc} = Calculated voltage between appliance frames and earth.
V_{fe} = Measured voltage between appliance frames and reference earth electrode.
Values given in parentheses are the measured results after adjustment for normal system voltage.

apply in all instances, it does normally tend to make conditions safer under broken-neutral conditions.

(*d*) Test No. 3, with the neutral broken at A, shows that the highest voltage measurable between frames and earth at Cartchief Nook Farm is 35 volts, corresponding to 70 volts with normal voltage applied to the system. Other measurements taken at the same premises are shown in Table 7 and it will be noted that there is little risk of serious shock even with the distributor neutral broken.

With breaks in the neutrals of the service lines to Cartchief Nook and Slack Farms, further tests were taken with potentials of 90 and 60 volts, respectively, applied to the system. The results are shown in Table 8 and, bearing in mind the results summarized in Table 7, it will be seen that the overall risk of shock throughout the system is not great. The beneficial effect of an earth electrode at each consumer's premises is again clearly shown.

(20) COMMENTS AND CONCLUSION

The experience of the North Western Electricity Board with protective multiple earthing under the present regulations between 1949 and 1956 is considered to be entirely satisfactory. No breakage of a distributor or service neutral has been recorded during this period, but tests and calculations on typical systems have shown that, if neutral breakages do occur, the danger of shock will be less than with other methods of earthing which have been commonly used.

It has not been considered necessary to ask the consumer to sign an indemnity on account of his use of the Board's neutral conductor for earthing purposes. Similarly, no indemnity is required when an earth connection is made to the sheath of a service cable on a completely underground metal-sheathed cable system, but it is the Board's practice to request an indemnity when an overhead earth wire or an earth-leakage circuit-breaker is provided.

The co-operation of the Ministry of Power and the concurrence of the Postmaster General in regard to minor relaxations of the p.m.e. regulations, shown by service experience to be desirable, has been greatly appreciated and has assisted in ensuring safety without wasteful expenditure. It is the view of many engineers that the revision of the p.m.e. regulations in 1949–50, together with these subsequent minor relaxations, has done much to reduce the practical and economic difficulties associated with the earthing of systems and equipment in rural areas.

(21) ACKNOWLEDGMENTS

The paper was produced because of a suggestion that it would serve a useful purpose to record, for the benefit of others, the experience of the North Western Electricity Board in the use of protective multiple earthing and the circumstances which led to its adoption on a widespread scale.

The author is indebted to numerous colleagues at the Headquarters, Sub-area Offices and District Offices of the Board for their assistance in compiling the necessary information. He is also indebted to Mr. H. G. Bell, Chief Engineer of the North Western Electricity Board, for permission to publish the paper.

DISCUSSION ON THE ABOVE PAPER

Before the SUPPLY SECTION 20*th November*, *the* SOUTH MIDLAND SUPPLY *and* UTILIZATION GROUP *at* LEEDS 21*st October*, *and the* MERSEY AND NORTH WALES CENTRE *at* CHESTER 25*th November*, *and the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER 26*th November*, 1957.

Mr. H. W. Grimmitt: It is well over 20 years since Dr. Taylor first started his work on earthing at the British Electrical and Allied Industries Research Association, and the result of that initial work is to be found in this paper. It also seems strange that the late A. P. Trotter, in 1902 in this building, said that it was very lucky that he had nothing to do with earthing, because the Board of Trade had no regulations regarding the method of earthing. This was during a heated discussion on whether the inner conductor of a 3-wire system should be earthed. What seems odd to me is that ever since I have had anything to do with the business, since 1930, there have been a lot of regulations on earthing.

The paper very usefully sets out the vicissitudes of the conditions required when installing p.m.e. These conditions took about six years to produce, and I now think that they are reasonable and practical; in a large measure this has been due to the author. He has treated the regulations with a sympathetic intelligence which one does not normally get with regard to regulations.

The problem of the broken neutral is present whether there is p.m.e. or ordinary earthing. Should a neutral conductor—say a service wire—break at the pole, it falls on something that is a bit of an insulator. Anybody coming along and touching it can be killed. I know of only one accident with the neutral breaking at the pole and falling on to a privet hedge separating two front gardens. A lady coming out of the house took hold of the neutral and was unfortunately killed. I do not think that this type of accident can possibly be prevented, but it has only happened once in 30 years.

The author's tests bear out very closely the tests done by the E.R.A., in which there were many more consumers and a lower resistance of the neutral to earth. The neutral was never above 30 volts. The small areas of rural development tested by the author are worse and present more difficult problems: the more premises there are the better.

In this country we do not have many fatal accidents. In fact, over the last 9 years domestic fatal accidents reported to the Ministry—not factory or mines accidents—average about 56 a year. Breaking down the reasons, we find that a high-resistance path was a contributory factor only in one or two each year. There are, however, broken earth-continuity conductors. There are also switches in the neutral and disconnected earth wires and so on, but we do not get many accidents due to a high earth impedance. It is also interesting to note that the average fatal-accident rate among the general public is 16 per year, the majority being caused through mobile cranes and people coming in contact with overhead lines, and things like that. There is only one accident here and there in which earthing is a contributing factor. It is interesting to note that, in 1949, 50 people were killed in domestic premises. The figures for the following years to date are 50, 54, 54, 64, 48, 53, 66, 51 and 59. In this period the number of consumers has almost doubled, and there is now electricity in nearly 12 000 000 houses. A death is always serious, but it cannot always be avoided, no matter how stringent are the regulations. In this country generally we are very fortunate, but I do not think we should therefore say that protective multiple earthing is unnecessary, or that we should not be very careful. However, what we have in this country is sound workmanship, and there I thoroughly agree with the author.

In the course of 30 years of inspections I can think of only four occasions when an electricity undertaking has had to be directed to do some work owing to bad workmanship. Regarding safety, good workmanship is vital, and care must be taken with details such as clamps and conductor bindings. One must always be alert.

The paper represents about 10 years' careful work. I am very pleased that the author has set it out in the way he has done, because it gives a correct and proper picture, and the North Western Electricity Board now have a practical system. I should, in closing, like to commend the Board for their broad-minded policy in this matter.

Mr. S. J. Emerson: I agree with Mr. Grimmitt that the standard of installations in this country, including the earthing connections, is high. There are more than 350 000 factories employing more than 25 persons in the United Kingdom, and last year there were 40 reportable electrical fatal accidents. I also agree with the author that, since no faults occurred on his networks, p.m.e. in his area was satisfactory.

The author refers to Acts of Parliament, and Mr. Grimmett enlarged on the Electricity Act of 1882; I agree with him. However, we must also consider the Factory and Workshop Act of 1901, since with p.m.e. there is a possible hazard which might be brought into the factory. Earthing under the 1901 Act is not necessarily the same as earthing under the 1882 Act. Under the former it means connecting to the general mass of earth in such manner as will ensure at all times an immediate discharge of electrical energy without danger. The earthing must be such that, on a fault, the fuse must blow or the circuit-breaker open under conditions of safety. General practice in Germany, where they have experience of a version of p.m.e. called *Nullung*, assumes that the metalwork must not rise more than 65 volts above earth before serious danger to persons is incurred. In Britain there is no definite safety figure for alternating voltage, but a lead of 40 volts is given by The Institution in its Regulations.

Fig. A shows that the lower the shock voltage the higher the

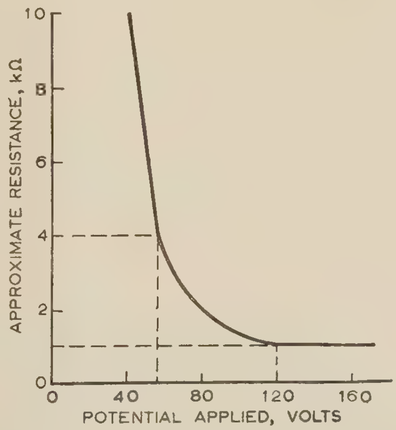

Fig. A.—Variation of human-body resistance with applied voltage.

resistance of the human body. This illustrates the importance of limiting the shock voltage.

Now, assume that an overhead phase conductor falls and makes fortuitous contact with a fairly low-resistance earth, such as by falling into a canal—the potential of the neutral will rise above earth, as will that of the consumer's apparatus. The Germans assume that the fortuitous earth fault is unlikely to be less than 5 ohms in resistance, and from this they deduce (see Fig. B) that the overall resistance of the neutral to earth should not be less than 2 ohms with *Nullung*.

This shows why I have misgivings regarding the figure of 10 ohms.

The author refers to the ratio of the earth resistances on the two sides of a broken neutral; he does not, however, place full emphasis on this point. There will be a considerable potential at the broken neutral (Table 5, line 4) with a break at B. This

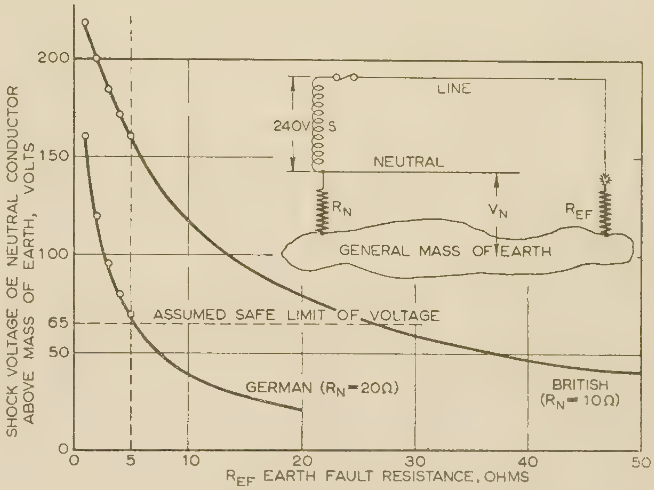

Fig. B.—Comparison of British and German systems.

S = 240-volt secondary winding of supply transformer.
R_N = Overall resistance to earth of neutral conductor.
R_{EF} = Earth-fault resistance of a line faulted to a low-resistance earth.
V_N = Rise of potential of neutral conductor above general mass of earth.

break could equally well occur between Consumers 1 and 2 (Fig. 6), in which case Consumer 1 would have metalwork raised above earth potential by some 150 volts. The important point to remember in connection with p.m.e. is that, wherever there is a break in the neutral, if the ratio between the earth resistances of the two sections is great, a high potential will appear somewhere in the system.

The author dismisses differential-current earth-leakage circuit-breakers summarily. Consider a factory on a p.m.e. system having hazardous situations necessitating flameproof equipment; a fault to earth would of necessity be a high-resistance fault with risk of fire or explosion. To discard the use of differential-current earth-leakage protection is not in the best interests of safety, and any country garage might be a case in point.

I believe that p.m.e. has great possibilities, but we must not at this stage rule out other developments, particularly where small rural factories, taking a medium-voltage supply, are concerned.

Mr. H. C. S. Hayes: The majority of telephone circuits are two-wire (we can neglect long distance trunks, most of which are worked carrier). These two-wire metallic circuits have to transmit not only speech, but also supervisory signals for calling, clearing, dialling, metering, coin-box discrimination, etc. To give all this over one pair of wires sets a problem which often is met by use of earth as an additional conductor. It is no exaggeration to say that most circuits have connection with earth at one or both ends. A circuit with connection to earth is very susceptible to any direct pick-up of 'local earth potential' and to any induced longitudinal e.m.f. It can be adversely affected in two ways:

(*a*) There may be interference with any earth-connected signals.

(*b*) Unless the two conductors of the telephone circuit have perfect balance with respect to earth—an ideal rarely attainable—a transverse voltage will be produced between the two conductors and harmonic frequencies of the power supply may cause noise.

The p.m.e. system has more than one connection with earth, and so in some degree current will leave the circuit for earth at one point and rejoin it at another. Within the earth-resistivity area of an electrode this gives rise to local soil potentials. In addition, the vector sum of the current flowing in the overhead conductors plus the neutral is not zero and a magnetic field therefore radiates from the system. If it happens that a Post

Office line has an earth connection within the resistance area of a p.m.e. electrode, or runs parallel to the p.m.e. system, it will be affected in some degree.

Having established that there are potentially dangerous conditions for a telecommunications circuit arising out of p.m.e., it is right that the Post Office should be cautious in regard to this system, and its growth must be watched closely. It is pleasing to report that, so far, the Post Office has not experienced any trouble from noise or otherwise which could be attributed to p.m.e.

Another aspect of p.m.e. which should be mentioned is the possibility of electrolytic damage to cables and other buried metallic structures. Some radio and television sets (and other apparatus, too) are in the nature of half-wave rectifiers, and when in use they introduce a measure of direct current into the normal a.c. system load. In the p.m.e. case there may therefore be some d.c. returned through the earth. While there is no positive evidence that there is trouble on Post Office plant arising from this, it is a facet which must not be entirely disregarded.

Mr. J. A. Robbins: One aspect of p.m.e. not yet mentioned is that it can increase installation fire risks—surely a retrogressive step. Official records pinpoint undetected earth-leakage currents, particularly in association with gas pipes, as a prolific cause of fires, yet p.m.e. cannot detect high-resistance faults. Furthermore, it deliberately encourages the flow of heavy currents on dead earth faults, which again increases the fire risk. Is it significant that countries tending to favour p.m.e. do not in general use coal gas to the same extent that we do?

The paper gives an erroneous impression that, with p.m.e., 100 volts on accessible metalwork is safe, owing to reduced p.d.'s inside the premises. This phenomenon is common to all electrical installations, and is one of the reasons why there are so few electrical fatalities. Nevertheless, 40 volts in a cowshed can cause expensive livestock fatalities.

Another point glossed over in the paper is the dangers which may arise from unauthorized extensions to installations, particularly where earthed metalwork is not correctly bonded to the neutral; this factor assumes increasing significance as the installations age.

Other methods of protection, capable of detecting high-resistance faults, have been summarily dismissed on highly debatable grounds. With circuit-breakers it is suggested that considerable testing is required; alternatively, that they have insufficient sensitivity. I challenge both statements very strongly. In addition, I would query the cost figures quoted in Section 14. The total cost per consumer, allowing for earth electrodes, seems to be about £10. This is not cheap compared with the average total installed cost—about £5—of a voltage-operated earth-leakage circuit-breaker.

Finally, it seems that the relaxations outlined in Sections 11(*c*) and 11(*d*) are effectively contradicted by comments in Sections 19.2(*c*), 19.1(*a*) and 19.1(*b*). Thus, practical experience has proved the wisdom of Dr. Taylor's original requirements.

Mr. E. C. I. Macdonald: Has the North-Western Electricity Board had any difficulty in dealing with the protective problem which arises from discontinuities in the neutral conductor of the distribution line?

It may be of interest to record that p.m.e. is now widely used in north-east Scotland, where earthing conditions in the rural areas are notoriously difficult. This development is comparable with that outlined in Table 2 and comprises upwards of 1 500 separate p.m.e. installations supplying an average of about three consumers each. After early experiments undertaken under the more onerous approval conditions it was decided to install a butt earth at every l.v. pole except transformer poles. This was a compromise between continuous earth-wires and the expense of augmenting the earthing after completion. It has only recently become practicable to undertake any considerable amount of earth-resistivity testing. The butt earths, which consist of No. 6 s.w.g. copper, are connected with the aluminium neutral conductor through a bimetal tap, and where necessary the earth-wire in the ground is protected by tape or a plastic tube. It is found that some 10–12 butt earths on any given system bring the total resistance to earth within the requirements without further expenditure, but where augmentation is required, copper strip or wire is buried 18 in below the surface as far as possible in non-interfering positions. L.V. neutral earths consist of stakes connected to the neutral by $0{\cdot}06\,\text{in}^2$ conductor insulated below ground level.

As the author has found, isolated premises provide the most difficult earthing problem, but suitable water-supply installations are not common in the Scottish areas mentioned. The cost of a local low-resistance earth may be as much as 25% of the cost of providing an isolated supply.

Mr. G. H. Fowler: I notice that, if the consumer is allowed to use the Board's neutral or the sheath of a metal-sheathed cable as his earth, no indemnity is required; but one is needed if he uses an earth-leakage circuit-breaker. Is there any logical reason for the distinction in obtaining an indemnity depending upon the method of connection? Is it considered that the risk of a fatality when the neutral or sheath is used is less than that with an earth-leakage circuit-breaker, or is there a basis in law, namely that the Board does not attract a risk if the consumer is allowed to use the neutral as an earth, but a risk is attracted if the consumer is allowed to connect apparatus to earth?

Mr. G. S. Buckingham: I should like to pay my tribute to the North Western Electricity Board for accepting responsibility, since 1953, for the provision of a good earth connection for their consumers' use. We in the Midlands Board do not accept that responsibility, which we have in the past regarded as rather onerous. We have been very impressed with the results obtained with the p.m.e. installations in the North-Western area, and we propose to extend its use considerably in the Midlands.

Fig. 3 shows the earth connection as an armoured but uninsulated cable. I cannot understand why such a construction is necessary, and should be grateful if the author would explain the need for it.

I think that the p.m.e. system, if it is sound, is completely safe, in spite of what Mr. Emerson and Mr. Robbins have said. By devoting so much time to describing tests under broken-neutral conditions, the author may have given the impression that this frequently occurs. Such is not the case. A broken neutral is a fault, and in any other system of earthing is likely to give more trouble than with p.m.e. In the p.m.e. installation there is a second line of defence, and the danger is still quite small. It is not negligible: 50 deaths a year cannot be ignored. We must not be complacent about that, but so long as the system is good we shall not have them, and that is the most important thing that emerges from the paper.

In domestic installations it is the custom to use two conductors and an earth wire. I feel that we should be logical and carry the 2-wire p.m.e. system right up to the consumer's socket-outlet or lampholder. Using the neutral conductor of the wiring installation as the earth conductor would be more reliable than running two main conductors and a separate, but usually smaller, earth wire.

Mr. E. Bramald (*at Birmingham*): The author has said that safety has been ensured by p.m.e. without wasteful expenditure. In addition to economies brought about by the Board, has there been any saving in consumer wiring costs? Has any use been made of earthed concentric wiring?

Individual substation neutrals are bonded to earth and in large urban areas the outgoing cable sheaths are also bonded at intersection link boxes to the cable sheaths from other substations. Thus, in one large area a grid is thereby formed of several hundred neutrals in parallel and in permanent connection with the general mass of earth. Consumers are permitted to use the service cable sheath for earthing, and if the neutral and cable sheaths were bonded together at remote ends, in addition to the existing bonds at each substation, ideal conditions would be obtained for the use of neutralization. I should like the author's views on this.

In Section 7 the author mentions the possibility of neutral breaks where neutralization is in use. Has he any records of such neutral failures on underground systems? If so, at what point in the neutral has failure occurred? If this has been brought about by tension at joints, cannot this be avoided by ensuring that phase joints open first. In any case, such failures in distribution neutrals are revealed immediately by behaviour of apparatus or lamps. The coincidence of apparatus insulation failure or other calls on the neutral to pass heavy fault current, thus leading to danger, is very remote.

Recently a considerable quantity of insulated twin concentric cable has been installed locally, showing a saving of some 10% over standard types. We are now considering installing m.i.c.s. cable and using the hard metal sheath as the neutral conductor, and we expect a 25% reduction in costs over conventional 2- and 4-core paper/lead cables. These cables have insulated outer conductors, because they are connected to a public supply system not subject to a consent for p.m.e.

If, however, a neutralized system were in use, a further substantial reduction (30–40% on paper/lead) could be made by omitting the neutral insulation. In the circumstances, this neutralization would cost the Board practically nothing. I am certain that were the Boards able to obtain permission for neutralizing in this way, the use of concentric cable for installation work would bring about a substantial national saving on materials. There would no longer be a necessity to run a third earth wire—which is all too often ineffective when most needed.

Generally, the present type of hard-metal-sheathed cables would create problems when used in domestic installations, but I have recently been able to gain the interest of a maker willing to manufacture a concentric house wiring cable similar to the old Stanos system, but there are one or two difficulties to overcome with accessories. With p.m.e. or neutralization, such systems could reduce the cost of wiring considerably. I shall be pleased to learn whether the author has similar views.

I visualize using concentric 2-pin plugs not unlike telephone jacks. The flexible leads to apparatus would be coaxial, with a light plastic sheath after the fashion of television leads, the outer utilizing the same amount of copper as would be used in both the neutral and earth wire of standard flexible cables. This would ensure a sound neutral, since any strain break would occur in the smaller phase conductor first. The simple construction of both cables and accessories should show a substantial saving and promote the use of larger numbers of sockets which, with the use of the fully protected flexible cords I propose, should make for a reduction of accidents due to such causes as broken earth-wires.

Mr. R. H. Rockliffe (*at Birmingham*): In connection with the provision of the earthing block referred to in Section 1.3, were any tests carried out to determine the effectiveness of the earth connection provided, was the test applied at each and every new consumer's premises, and were any random checks taken afterwards to ascertain whether there had been any deterioration of the earth connection provided?

One of the requirements of protective multiple earthing, which is referred to in clause (*f*) of Section 8, is that the neutral conductor shall be of the same material and cross-section as the phase conductor. If this requirement were altered to read: 'The neutral conductor shall have at least the same current-carrying capacity as the phase conductor', then 3-core cable distributors could be used, the sheath acting as neutral. This could effect considerable economies in distribution practice, and I should like the author's comments on this point.

Mr. A. G. Lyle (*at Birmingham*): Emphasis has been laid on the need, for the preservation of overall safety, of a low earth-electrode resistance provided cheaply. If

$$R = \frac{\rho}{2\pi l}\log_\varepsilon\frac{2l}{r}$$

where R is the earth-electrode resistance, ρ the resistivity, l the buried length of the electrode, and r its radius, it is clear that the lower the resistivity and the longer the buried length, the lower will be the earth-electrode resistance.

The water table may easily be 3 ft below ground level and, if it is, not much of the electrode can tap the low-resistivity earth below the water table. In these circumstances, and in the absence of a fortuitous water pipe, it may be worth while to consider the vertical burial of the earth stake by the process of 'jetting'. This operation requires a centrifugal hydraulic pump to force water at a pressure of 80 lb/in^2 or more through a cage at the foot of the pipe. It is a relatively simple and speedy matter to sink a 2 in diameter pipe 20–30 ft vertically in ground which is not too rocky. Burial to a depth of 30 ft yielded a resistance of the order of 7 ohms in a random position in the unpromising Iraqi desert, but in this case the holes were drilled as for an oil well and not by 'jetting'.

Mr. D. A. Picken (*at Chester*): Breaking of the neutral conductor is not unknown, and on what I believe was the first substantial p.m.e. system in this country, namely that at Barley on the Nelson Corporation system, a broken neutral was experienced. This was the result of damage to a pole by a road vehicle, and I have had occasion to investigate a fatality to a child when an overhead neutral service conductor broke and fell to the ground, although this was on a normal system.

In areas of high resistivity, such as the slate-mining areas of North Wales, it has seemed to me that 'earthing' of the neutral and attempts to earth apparatus have introduced a hazard which would not exist if the system were unearthed, provided that precautions were taken to prevent the l.v. system being energized from the h.v. system, and I should welcome the author's comment on this problem in the light of experience his organization may have gained as a result of operation in the slate-quarrying area of Cumberland, although this is probably not so extensive as that of North Wales.

Mr. R. D. Haigh (*at Chester*): The large number of separate earth points which occur on p.m.e. systems may give rise to difficulties if different electrode materials are concerned. Such materials in fairly close proximity, metallically connected, must form an electrolytic cell and so lead to corrosion of one or other of the electrodes. Have any such cases arisen in the systems under consideration?

I can bear out the statement of a previous speaker that multiple earths can cause increased hum on communication circuits when circulating currents in the earth loops formed induce 50 c/s voltages in the input circuits of amplifiers connected to the power system. The solution is to connect the screens of all the amplifier equipment to a single earth point.

Mr. A. R. Raven (*at Manchester*): The author claims that the most important fact resulting from the investigations is that detailed testing was unnecessary, since it had been shown that calculated and practical results show close agreement. This

would be valid if the tests constituted a full statistical investigation, but I doubt whether the author would claim this. However, if the tests have shown that the worst possible conditions indicate that a full statistical inquiry is unnecessary, the deduction will still hold. Does the author consider that he has covered the worst possible case, or cases which are sufficiently close to this category, to justify the conclusions?

The author refers to 'typical p.m.e. systems'. I doubt whether there is such a system, and consider that each must be judged upon its own merit. The concept of a typical system presumably leads to the conclusion in Section 19.3(*b*), but how can electrodes be arranged relative to a neutral-conductor break in practice? It would appear to me that the disposition would be purely fortuitous.

The p.m.e. regulations require separate earthing of h.v. and l.v. sides of supplies to a p.m.e. system; presumably this carries on from B.S. 1320 practice, where the need can be fully appreciated. If, however, on a p.m.e. system l.v. neutral overall resistance is low—and it should be no more than 2 ohms—the best overall protection could be obtained by bonding the h.v. and l.v. earths; for example, with separate earthing, a lightning surge on the h.v. line could cause a high voltage to appear on the l.v. conductors by flashover of the transformer l.v. insulation if the h.v. earth were of high resistance. This voltage could appear at an l.v. consumer's terminal and cause failure of equipment, especially if the transformer l.v. earth resistance were high and a nearby consumer's earth resistance were low.

In Section 15 the author mentions the possible danger to cattle from voltage gradients near to positions where earth conductors enter the ground. If the overall resistance to earth of the p.m.e. system is low, as mentioned above, is the precaution of insulating the earthing wire necessary? There is, however, another reason why such conductors should be protected where they enter the ground: footpaths and lanes in rural districts often have a cinder surface, and I know of large conductors being completely corroded at such positions from this cause.

Mr. A. Hopkinson (*at Manchester*): If plastic-insulated and sheathed distribution cable is used in urban distribution systems and p.m.e. is employed, it will be difficult if not impossible to comply with the present regulation which requires that at each supply transformer the earth electrode for the lower-voltage system shall be outside the resistance area of that for the metalwork associated with the high-voltage system.

It appears from Table 7 that the metal fireplace at Cartchief Nook Farm was not bonded with an earth-continuity conductor, and the tests indicate that such metalwork should be included in the earthing arrangement.

I agree that, although the relaxed regulations do not require an earth electrode at each consumer's premises, it is advisable to have one.

The point concerning the equality of the resistances of the first low-voltage earth electrode and that situated near the end of the line is interesting and has probably not been appreciated in the past.

The regulation for testing the earth-continuity conductor indicates that a testing current of not less than 10 amp should be applied for a period of not less than 5 min. Should not alternating current be specified?

Mr. J. Tozer (*at Manchester*): It is interesting to note that the majority of the tests were carried out at premises which had a local earth electrode, and it is clear from the paper that this is definitely beneficial whether a p.m.e. system is installed or not. This is not in line with point (*d*) in Section 11, and it would be advantageous if this point were emphasized more strongly.

Mr. E. Roscoe (*at Manchester*): Telegraph engineers were the first to use the earth as a conductor of electricity, thereby saving the cost of a wire for the return currents. The power engineer followed the same practice for leakage, or fault, current. In many cases false economy has lead us into difficulties. Why do we earth?

The broad answer is: for safety reasons, but the more precise reasons are:

(*a*) To limit the voltage difference of the system from that of the general mass of earth.

(*b*) To ensure that the protection will operate under fault conditions.

Since the resistance path to and through the earth is often high, a metallic path in the form of a conductor is necessary to ensure operation of the circuit protection. Protective multiple earthing is often a cheap method of providing such a path, especially on existing normal distribution systems. The only difference between the normal system and p.m.e. is that the neutral is joined to the protective metalwork of the consumer's appliances, and is earthed at a number of points. I suggest that on normal systems the neutral is accidentally joined to earth at a number of points on the consumer's installation, and may be on service cables, owing to contact of the neutral conductor with earthed metal. The earth-continuity conductor is connected to the protective metal of appliances and to earth, which, when earths do appear on the neutral, produces a p.m.e. system on the normal distribution system.

Since we have not had trouble from such an arrangement, I should like to ask the author two questions:

Would it not be safer to earth the neutral at a number of points on all systems deliberately, and to connect the protective metalwork direct to earth, rather than to neutral?

Does he consider that the passing of 10 amp for 5 min along the earth-continuity conductor is worth the trouble compared with 180 amp by a phase-earth loop test?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. F. Mather (*in reply*): For brevity I will deal with each speaker individually.

Mr. Grimmitt has stated the national position clearly and his guidance has always been valuable.

Mr. Emerson.—When there is a break in the neutral, the system voltage is divided into three components: one appears across consuming devices beyond the break and the others appear between neutral and earth on each side of the break. If the first component is high, the others, which determine the shock risk, are correspondingly low. The advisability of making them as nearly equal as possible is stressed in the paper. Regarding Fig. 6 and Table 5, the earth electrode at consumer 1 was disconnected for this test but would normally be effective in case of a break in the neutral between consumers 1 and 2.

Mr. Hayes has given a most useful explanation of the point of view of the Post Office.

Mr. Robbins.—The costs applied before various relaxations were granted, but p.m.e. is normally much cheaper than earth-leakage circuit-breakers or continuous earth wires.

Mr. Macdonald.—No difficulties have been encountered from discontinuities in distributor neutrals on p.m.e. systems in the N.W. Area.

Mr. Fowler.—It was considered that the risk of failure of the cable sheath or neutral of a p.m.e. system was so small that

indemnities were not warranted. Experience indicated that this did not apply to systems employing earth-leakage circuit-breakers or overhead earth wires.

Mr. Buckingham.—Armoured and served uninsulated cable is well protected against mechanical damage and corrosion; moreover, it is so obviously part of the electrical system that it is less liable to interference than bare copper wire. Mr. Buckingham is right in saying that the danger of broken neutrals can be exaggerated.

Mr. Bramald.—I am not aware of any saving in consumer wiring costs arising from the use of p.m.e., but Mr. Bramald has pointed the way to cheaper and perhaps safer installations.

Mr. Rockliffe.—Many loop-impedance tests have been carried out and show that, in general, they are more necessary on overhead distribution systems than on underground systems using cable sheaths with plumbed joints. The reasons for requiring that the neutral shall be of the same material and cross-section as the phase conductor are to ensure that too large a proportion of current will not follow earth paths and that the neutral will not be more liable to break than the phase conductor.

Mr. Lyle.—The 'jetting' process may prove useful where extensive earthing systems are necessary.

Mr. Picken.—If a resistance of 10 ohms or less between neutral and earth cannot be obtained at reasonable cost, earth-leakage circuit-breakers or continuous earth wires, or a combination of both, should be used.

Mr. Haigh.—The only metals likely to form earth electrodes on p.m.e. systems are copper and galvanized iron. The electrolytic cell formed by these metals will cause corrosion of the galvanized iron only, and since this is generally extensive in area compared with the copper, it seems unlikely that trouble will result. No cases of increased noise in communication circuits due to p.m.e. have come to my notice.

Mr. Raven.—When stating that comprehensive tests are unnecessary on every p.m.e. system, I referred to tests under broken-neutral conditions. If all electrode resistances are measured, taking account of the large separation necessary to prevent overlap between extensive electrode systems and temporary test electrodes, the voltage distribution under broken-neutral conditions can be calculated with reasonable accuracy. The disposition of earth electrodes on p.m.e. systems is not completely fortuitous, and steps can often be taken to concentrate them towards the ends of the system.

It is debatable whether the insulation of down-leads to earth electrodes is important on p.m.e. systems, but the cost is small and there is the advantage mentioned by Mr. Raven.

Mr. Hopkinson.—It is not essential to use alternating current for the testing of earth-continuity conductors as mentioned in The Institution's Wiring Regulation 508(*c*).

Mr. Tozer.—Although the present p.m.e. regulations do not call for an electrode at each consumer's premises, the advantage of having one is shown in the paper.

Mr. Roscoe.—Circumstances may render it desirable to use p.m.e. on underground distribution systems in the future. The test current of 10 amp for 5 min is applied to the consumer's earth-continuity conductor and may reveal loose contacts in addition to measuring resistance or impedance.

621.314.2 : 621.374.32 : 681.142

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THE DIGITAL COMPUTER APPLIED TO THE DESIGN OF LARGE POWER TRANSFORMERS

By W. A. SHARPLEY, Associate and J. V. OLDFIELD, B.Sc.(Eng.), Graduate.

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SUMMARY

The paper describes an extensive investigation into the design of transformers with the aid of a high-speed digital computer. A general programme has been developed covering a range of transformers from 30 to 210 MVA, and has been tested for a wide range of designs within these limits. The subdivision of the process of design and its translation into a form suitable for a digital computer are described. Basic details of particular sub-routines are given to illustrate the problems of logic and arithmetic encountered. The techniques needed to control the design process within the computer are discussed, with special reference to the organization of data. A detailed description and derivation are given of the method used to obtain convergence to specified design characteristics without intervention by a designer. The results of several investigations concerned with the effect of changes to certain design parameters are included.

LIST OF PRINCIPAL SYMBOLS

B = Flux density, gauss.
D = Core diameter, mm.
d = Bare-conductor depth, mm.
e = Eddy-current loss expressed as a fraction of the I^2R loss.
P_f = Iron loss, kW.
I = Current, amp.
J = Current density, amp/mm^2.
k = Ratio (per section) : (horizontal surface area exposed to the cooling medium)/(total horizontal surface area).
P_l = Load loss, kW.
p = Iron loss per unit weight, watts/lb.
q = Dissipation, watts/mm^2.
t = Conductor insulation thickness, mm.
w = Bare-conductor width, mm.
W_f = Iron weight, lb.
X = Reactance, %.
η = Index of iron-loss curve.
ρ = Resistivity of conductor, ohm-mm.

Note.—Superscripts are to be interpreted as follows:
c = Calculated value.
d = Desired value.
I = Value for first iteration.
II = Value for second iteration.
e.g. P_f^{cII} = Calculated iron loss at the end of the second iteration.

(1) INTRODUCTION

In an earlier paper[1] the application of a digital computer to the design of rural-type transformers was outlined. A programme has now been written for the design of a wide range of large power transformers, using methods similar to those developed earlier, for use on Pegasus[2, 3] a high-speed 2-level-storage digital computer. It is intended to illustrate the manner in which a computer can be instructed to perform the various operations normally required of the designer, rather than to stress the features of the design method employed.

The scope of the programme is already quite wide, and is in the process of extension; at present it covers the following arrangements:

3-phase, with star or delta connections.
H.V. tap winding for high-voltage variation.
Core-type construction with three or five limbs.
Concentric cylindrical windings.
Winding order (from core): l.v., h.v. and tap.
Disc-type h.v. winding.
Layer-type l.v. winding.

The ratings covered are as follow:

Output: 30–210 MVA.
Input voltage: 6·6–22 kV.
Output voltage: 66–300 kV.
Tap range: up to 30%.

In order to take full advantage of the high rate of computation afforded by the computer, the complete design process has been mechanized, allowing the computer to take all the logical decisions required and avoiding any intervention by the operator.

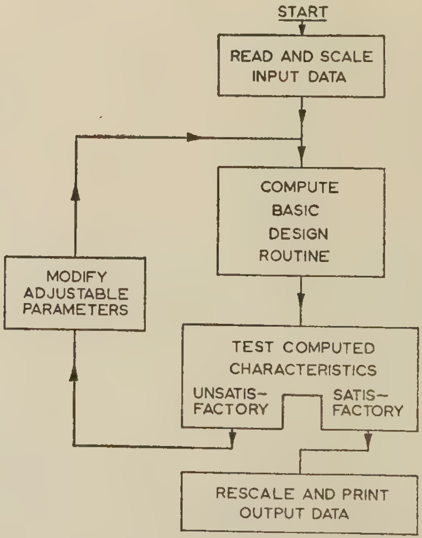

Fig. 1.—Simplified flow diagram for programme.

The programme has been subdivided for convenience in development and testing, the principal subdivisions forming the flow diagram in Fig. 1 being as follow:

(*a*) *Reading and scaling of input data;* an initial set of *adjustable parameters*, namely flux density, winding current densities (h.v., l.v. and tap) and core diameter is included in the input data.

Mr. Sharpley is with Bruce Peebles and Co. Ltd., Mr. Oldfield is in the Electrical Engineering Department, Queen Mary College, University of London.
The work carried out by Mr. Oldfield will form part of a thesis to be submitted for a higher degree of the University of London.

(*b*) *Basic design routine,* for computation of a complete design corresponding to a set of adjustable parameters. The result includes a set of *computed characteristics,* namely iron loss, load loss and reactance.

(*c*) *Comparison of the computed characteristics* with those desired. If the computed characteristics are within specified limits of the desired characteristics, the section for rescaling and printing of output data is entered. Otherwise, the adjustable parameters are modified.

(*d*) *Modification of the adjustable parameters* for the next iteration of the basic design routine, so as to cause the characteristics to converge to the desired values.

(*e*) *Rescaling and printing of output data* for the designs which meet the desired characteristics.

These subdivisions and the principles employed are discussed in greater detail in the following Sections.

(2) BASIC DESIGN ROUTINE

Since the basic design routine is very complex, it has been divided into 20 design sub-routines. Advantages of this method are that these sub-routines may be used directly in other design programmes and may be tested individually with a special test programme discussed in Section 10.2. The order of computation of the design sub-routines is set out in Table 1.

Table 1

ORDER OF COMPUTATION OF DESIGN SUB-ROUTINES

Connections
- Winding voltages and currents from line voltages, output rating and phase connections.

Design of core cross-sections
- Leg lamination widths for optimum leg area.
- Leg stack depths.
- Gross leg area.
- Yoke lamination widths.
- Gross yoke area.

Turns
- H.V. (minimum tap), l.v. and tap-winding turns.

Accommodation of h.v. (minimum tap) winding
- H.V. conductor dimensions.
- Number of sections and turns per section.

Accommodation of l.v. winding
- L.V. conductor dimensions.
- L.V. winding dimensions.

Accommodation of h.v. (minimum tap) winding (continued)
- H.V. winding dimensions.

Accommodation of tap winding
- Tap conductor dimensions.
- Tap winding dimensions.

Core weight and iron loss
- Weight of core.
- Iron loss.

Conductor weight and load losses
- Conductor weight of each winding and load losses for various taps.

Reactance
- Reactance for various taps.

Costing
- Prime cost of transformer.
- Total capitalized cost over life period.

Several sub-routines will be described in detail, in order to illustrate the special problems of logic and arithmetic encountered.

(2.1) H.V. (minimum tap), L.V., and Tap-Winding Turns Sub-Routine

The main difficulties in calculating the numbers of turns for the three windings lie in obtaining an integral number in each tap step without exceeding the maximum permissible ratio error on any tapping. One solution is to limit the number of turns per tap step to an integer equal in all steps, the numbers in the other windings then being calculated on this basis. However, the above procedure imposes undesirable and unnecessary restrictions upon the choice of turns and flux density for a given core area. A change of one turn in the number of turns per tap step, in general, produces a large change in flux density and an even larger change in iron loss. This gives rise to difficulties in convergence to a specified iron loss and economic optimization. The scheme adopted permits unequal numbers of turns per tap step, although preference is given to equal numbers. A more detailed description of the method is given below.

The following quantities are calculated and stored:

(*a*) Number of l.v. turns per leg, rounded to the nearest integer.
(*b*) Number of h.v. turns per leg on minimum tapping, unrounded.
(*c*) Total number of tap-winding turns per leg, unrounded.
(*d*) Maximum permissible error turns on maximum h.v. tap, unrounded.
(*e*) Maximum permissible error turns on minimum h.v. tap, unrounded.
(*f*) Maximum permissible total number of tap-winding turns, unrounded [(*c*) + (*d*) + (*e*)].
(*g*) Minimum permissible total number of tap-winding turns, unrounded [(*c*) − (*d*) − (*e*)].

Quantities (*d*) and (*e*) are determined from the maximum permissible ratio error. Fig. 2 represents diagrammatically

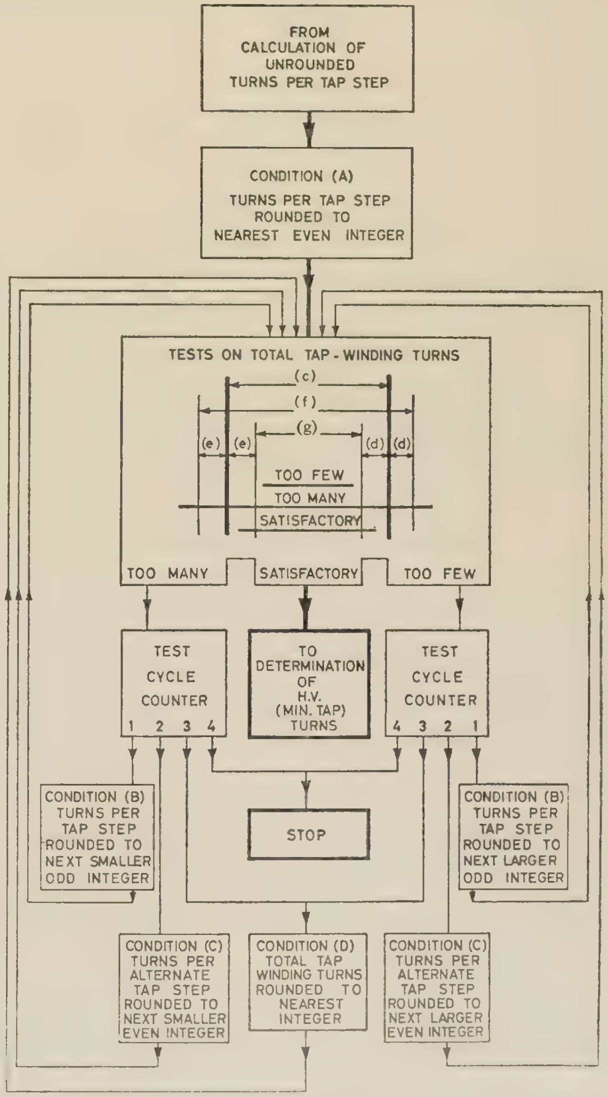

Fig. 2.—Flow diagram for rounding the number of tap-winding turns.

quantities (*c*)–(*g*). If the permitted ratio errors are not to be exceeded, it is evident that the number of tap-winding turns must lie between (*f*) and (*g*).

The programme is arranged to test the following conditions for compliance with the above requirement:

(A) Turns per tap step rounded to the nearest even integer.
(B) Turns per tap step rounded to the nearest odd integer.
(C) Turns per tap step rounded to odd and even integers in alternate tap steps.
(D) Total number of tap-winding turns rounded to the integral number nearest to (*c*).

The sequence of calculations and tests is shown in Fig. 2. The blocks entitled 'test cycle counter' cause conditions (A)–(D) to be considered in the above order of preference and also inhibit repetition. The two counters shown are coupled; if, for example, condition (B) has been tried [through (A) having too few turns] and is found to have too many turns, condition (C) is automatically considered.

When a satisfactory number of tap-winding turns has been obtained, the rounded h.v. (minimum tap) turns are calculated. Two alternative forms of rounding are tested in the following order:

(E) Number of h.v. (minimum tap) turns rounded to the nearest even integer.
(F) Number of h.v. (minimum tap) turns rounded to the nearest odd integer.

The ratio errors at maximum and minimum tappings are then checked to ensure that the maximum permissible errors have not been exceeded. This procedure is shown diagrammatically in Fig. 3. The counters control the order of selection of the two alternatives and prevent repeated cycling.

Finally, provision is made for the possibility of the total rounded number of tap-winding turns lying between (*f*) and (*g*) but, owing to the rounding of the number of h.v. (minimum tap) turns, the ratio error at either maximum or minimum tapping is excessive. In this case the number of tap-winding turns is modified to suit the next arrangement in the previously mentioned order of preference and the number of h.v. (minimum tap) turns and the ratio errors are recalculated. The whole cycle is repeated until an acceptable solution is reached or—in the extremely rare event of this being impossible—the computer is arranged to come to a programmed stop.

(2.2) H.V. (minimum tap) Winding-Conductor Dimensions Sub-Routine

The programme has been written for a disc-type winding, with provision for two alternative methods of separating adjacent sections, namely spacing blocks between all sections, and spacing blocks between consecutive pairs of sections, with washers between the sections of each pair. Either alternative may be specified or the choice may be left to the computer. The method of calculation to obtain the conductor dimensions ensures that the computed thermal dissipation approaches but never exceeds the specified maximum.

The quantities required prior to computation are:

(*a*) A parameter to indicate the type of winding structure: this has three possible values, namely 0 for spacers between all sections, 1 for alternate washers and spacers, and 2 the type to be determined by the computer.
(*b*) Resistivity of conductor.
(*c*) Current density (starting value).
(*d*) H.V. leg current.
(*e*) Eddy-current loss expressed as a fraction of the I^2R loss.
(*f*) Ratio (per section): (horizontal surface area exposed to the cooling medium)/(total horizontal surface area).
(*g*) Maximum permissible dissipation.
(*h*) Conductor insulation thickness.

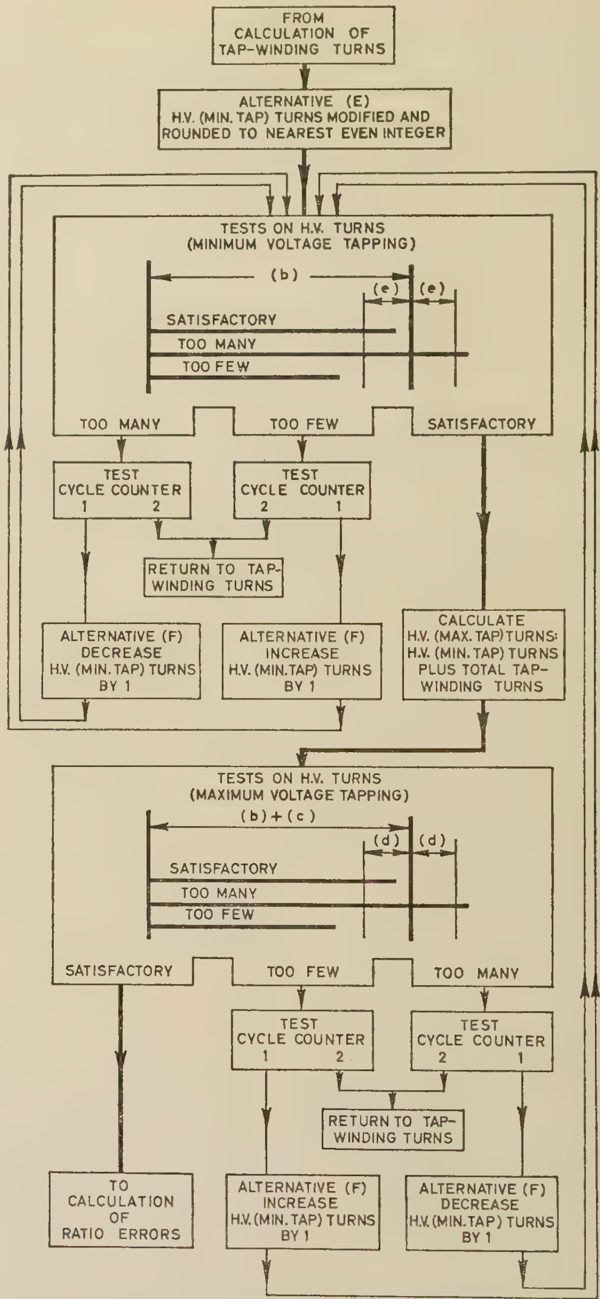

Fig. 3.—Flow diagram for ratio-error tests on h.v. winding: maximum and minimum tappings.

(*i*) Interval between the depths of consecutive conductor stock sizes.
(*j*) Interval between the widths of consecutive conductor stock sizes.
(*k*) Maximum permissible conductor depth.
(*l*) Maximum permissible conductor width.

The sequence of calculations is shown in Fig. 4. This commences with the determination of the covered conductor depth from input quantities (*b*)–(*g*), with the number of conductors in parallel initially set to unity; the following expression, derived in Section 10.1, is used:

$$(d + t) = \frac{\rho IJ(1 + e)}{2qk} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

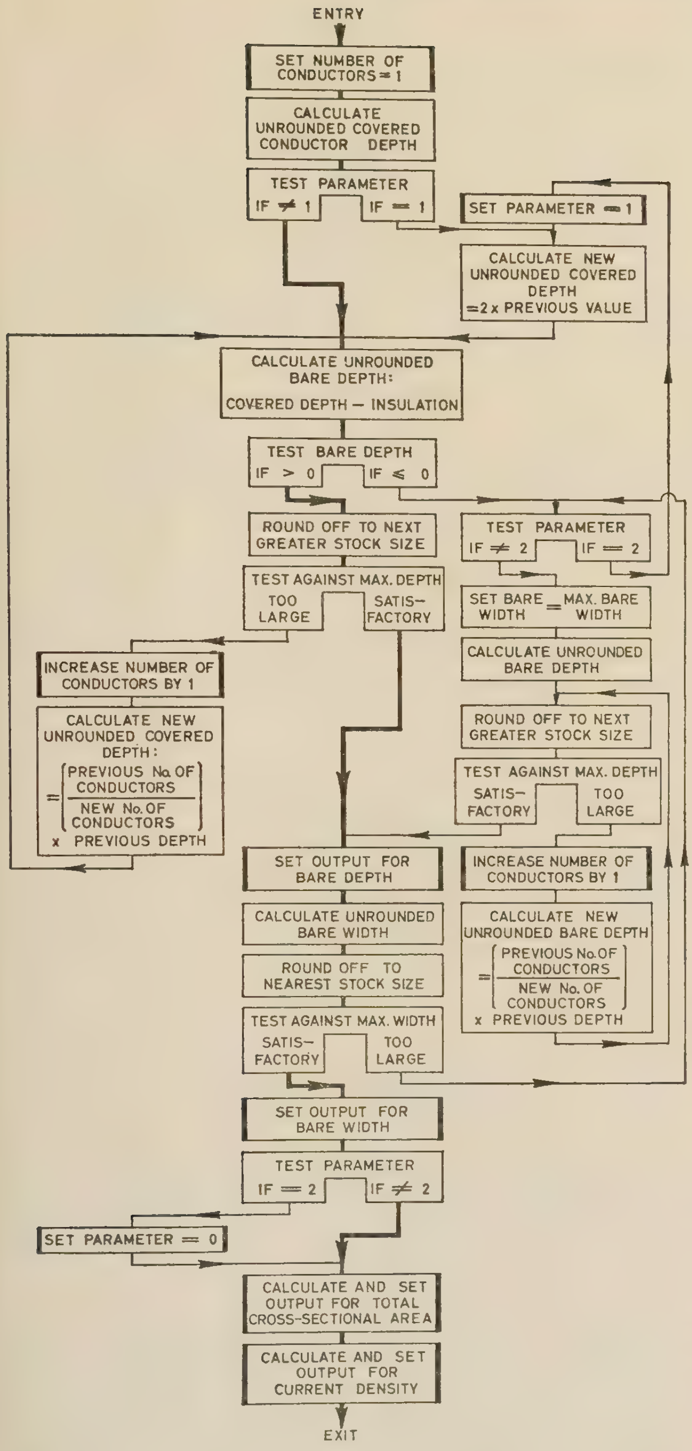

Fig. 4.—Flow diagram for h.v. (min. tap) conductor dimensions.
Blocks shown [box] indicate output quantities.

The parameter is then inspected to ascertain which type of winding structure has been specified, and further computation proceeds along one of the two paths shown. At appropriate stages in the calculation the computed conductor dimensions are compared with the specified maxima; if these have been exceeded the paths followed will cause such modifications as are required to reach satisfactory final dimensions.

The output quantities from the sub-routines are:

(*m*) Number of conductors in parallel.
(*n*) Bare conductor depth.
(*o*) Bare conductor width.
(*p*) Total cross-sectional area of conductor.
(*q*) Current density (final value).
(*r*) Parameter as (*a*), to indicate which arrangement has been found suitable if originally an optional winding structure was specified.

(2.3) Iron-Loss Sub-Routine

One method of calculating the iron loss by hand involves reference to a curve of iron loss per unit weight against flux density for the selected core material. In adapting this method for a digital computer it is necessary to translate the curve into numerical form. In a programme described in an earlier paper,[1] the loss curve was represented by a truncated power series, the coefficients for the series being supplied with the input data; the calculation of coefficients was carried out separately. It has now been found more convenient to represent each curve by a table of values of iron loss per unit weight, corresponding to a set of points at equal intervals of flux density. A sub-routine has been written for the computation of iron loss as follows:

(*a*) Determination of the upper and lower values of the interval containing the given flux density, and of the corresponding values of the iron loss per unit weight. If the given flux density is outside the range of the table, the computer will come to a programmed stop.
(*b*) Linear interpolation to determine iron loss per unit weight for the given flux density.
(*c*) Multiplication of the iron weight by the iron loss per unit weight to give the total iron loss.

The use of this method, with a table of only eight values, has proved sufficiently accurate for design purposes.

(2.4) Core Cross-Section Sub-Routines

A set of sub-routines is incorporated in the basic design routine for the determination of the optimum core cross-section corresponding to a given core diameter, i.e. so that the maximum iron area is obtained within the core circle. The method used is applicable to stepped circular cores that are externally clamped; the calculated lamination widths are restricted to stock sizes. An accurate value of the gross core area is calculated. This is of importance in the determination of the number of turns in each winding (Section 2.1), since the tap-winding arrangement may be considerably affected by small changes in core area.

An iterative method is employed to solve a set of partial differential equations relating the core area to the lamination widths. It is interesting to note that, although a graphical method of solution is known which avoids the iterative procedure, this is much more difficult to mechanize. The quantities used are core diameter, number of core steps (up to 16), stock size interval for lamination widths, minimum clearance for clamping structure (between outside laminations and core circle), width of ducts parallel and at right angles to laminations (if any).

(3) ORGANIZATION OF DATA

The arithmetical facilities of the Pegasus computer are such that, in direct operation, any number x is restricted to the range

$$-1 \leqslant x < 1$$

A programme (part of the initial-orders routine for Pegasus) is permanently stored on the magnetic drum, so that numbers within this range, punched on paper tape in signed decimal form, may be read by a tape reader and converted into binary form before being written into the main store. However, the range is inconvenient for transformer design, since units used in

hand computation have generally been chosen so that numbers lie within the range 0·01–1 000. At an early stage it was decided to reject hand scaling, because of its inconvenience and the possibility of errors. The restriction on range may be overcome by the use of programming techniques, and several schemes were examined before the present scheme was adopted.

By using floating-point sub-routines, floating-point arithmetic may be performed with a fixed-point computer. For instance, in one system, any number x may vary between the approximate limits of $-2\cdot 10^{78} < x < 2\cdot 10^{78}$ and $2\cdot 10^{-78} < |x| < 2\cdot 10^{78}$. This range is adequate for most scientific and engineering problems, the chief disadvantage being that the overall speed of the computer is reduced by a factor of at least three. The method is very valuable in problems where the range of values of specific quantities is very large, such as in matrix inversion, but it was felt that its use was not justified in the transformer design programme.

Another method considered was that of using a fixed scale factor for all design quantities, such that

$$-1 \leqslant \left(\frac{\text{maximum possible number encountered}}{\text{scale factor}}\right) < 1$$

All design quantities should then be within the range of the computer. It was found that a suitable scale factor would be of the order of 10^5. The use of this method would cause the overall precision of arithmetic to be low, owing to the loss of digits at the least-significant end of the accumulator. It would be most serious in forming the product of several small numbers.

In the method adopted each quantity in the design, both in input and output, has been assigned a scale factor, an integral power of two, chosen so that

$$-1 \leqslant \left(\frac{\text{maximum possible value of quantity}}{\text{scale factor}}\right) < 1$$

The indices of the scale factors are stored in the computer prior to the input of data. Numbers are read from the data tape, and each is scaled according to its scale factor by the input-data scaling sub-routine. A check is made to ensure that each scaled number is within the range of the computer before it is written in the appropriate main-store location. An important advantage of the method is that the scaling forms a check on the results as they are calculated, and mistakes in the programme or input data are usually revealed quickly and located easily. Although arithmetical operations are carried out to the equivalent of about 11 decimal places, the results are printed only to four significant figures, in order to save computer time while giving sufficient precision for design purposes. The arithmetical precision of the calculations is valuable in that the scale factors may be chosen to cover a wide range of designs without loss of significant figures in the results. The method has proved very convenient in use.

(4) CONTROL OF THE COMPLETE PROGRAMME

This Section deals only with those parts of the programme directly concerned with the control of the design process. The flow diagram of the complete programme is shown in Fig. 5. A special programming technique has been used in the section concerned with the computation of the basic design routine. The transfer of data between the main store (magnetic drum) and the computing store (nickel delay-lines) prior to and immediately after the computation of a design sub-routine is controlled by the master programme, which makes reference to a list of data transfers held in the main store. The list is known as the 'directory'. The technique provides several advantages, namely

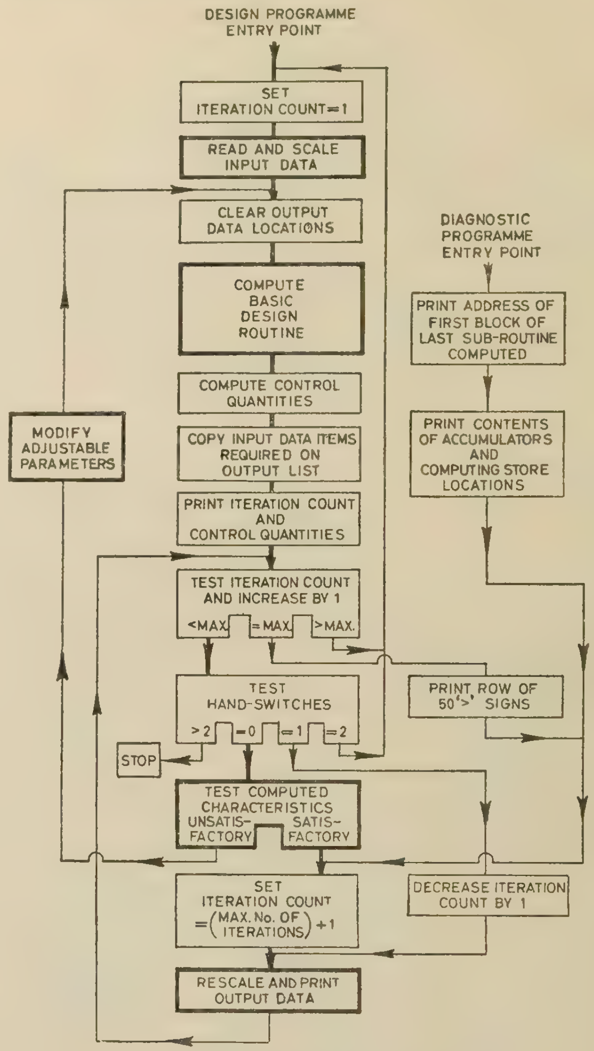

Fig. 5.—Flow diagram for computer programme.
Blocks shown ▭ indicate major sections.

(*a*) Data storage allocations in the main store need not be made until all the design sub-routines have been programmed and tested.
(*b*) Design sub-routines may be used in different design programmes without modification.
(*c*) The preparation of the directory is straightforward process which may be checked easily.

At the end of each iteration a limited number of control quantities are printed to demonstrate the progress of the design. For instance, the iron loss, load loss and reactance are printed as per-unit values of the desired characteristics and these are used to determine whether the design is satisfactory. If so, the complete design is printed and more data are read from the input tape to start the next design; if not, the modification section is entered. Although most designs converge very rapidly, as a precaution the iterations are counted, and if a preset number is reached, the latest computed design is printed, preceded by a row of '>' signs which can be detected easily in the output tape. Provision has been made for operator intervention by setting certain hand-switches, the settings being interpreted as follows:

0 : No intervention.
1 : Print the latest design computed.
2 : Read more data from the input tape before recommencing design.
3 or more : Stop (unassigned settings).

(4.1) Diagnosis of Programme Failure

Owing to the length and complexity of the programme and the high speed of computation, special precautions have been taken to facilitate detection of programme failure, and subsequent diagnosis; this may be due to mistakes in the input data, programming errors, the use of the programme for a design outside its scope, or a computer fault. Four methods of checking have been found useful and are discussed below.

(4.1.1) Tests on Scaled Input Data.

After being scaled by the input-data scaling sub-routine, each design quantity is checked (as indicated in Section 3) to ensure that the scaled value is within the range of the computer. If any number fails to satisfy this check the computer comes to a programmed stop.

(4.1.2) The Overflow Indicator.

The Pegasus computer contains equipment for detection of overflow, and the order-code includes conditional jump orders based on the state of the overflow indicator. If any number in any operation exceeds the range of the computer, the overflow indicator will be set. At the end of each design sub-routine the indicator is tested, and if it is set, the 'overflow print' sub-routine is entered. This is designed so that a special symbol signifying overflow is printed, followed by the reference number of the design sub-routine. Afterwards the computer comes to a programmed stop.

(4.1.3) Programmed Stops.

In certain design sub-routines special checks are incorporated, e.g. the iron-loss sub-routine (Section 2.3) includes provision for stopping the computer if the flux density falls outside the range of the iron-loss table. Other design sub-routines contain tests to cause programmed stops if called in for tasks outside their scope: for instance, the core-weight sub-routine is at present limited to 3- or 5-limb cores; if any other number of limbs is specified, a programmed stop occurs.

(4.1.4) Track Number Lights.

The surface of the magnetic drum used as the main store is divided into a number of tracks. Lights on the operating panel indicate the number of the track last concerned in reading or writing operations, i.e. in transfer of data or programme to or from the computing store. In normal operation the track number changes frequently, and it is easy for the operator to detect programme failure by watching the track number lights. If a stop occurs, or the computer continually loops round a group of orders, the track number will remain constant.

(4.2) Diagnostic Programme

A diagnostic programme is incorporated in the complete programme, so that if programme failure occurs the operator may cause significant information to be printed for use in determination of the cause of the fault. The programme is entered by orders set on the hand-switches on the operating panel. The following information is printed:

(a) The word 'stop' followed by the main-store address of the first block of the latest design sub-routine computed.
(b) The contents of the accumulators and the computing store, printed as decimal fractions to six places,
(c) The rescaled output data.

The output-data storage locations in the main store are cleared before each design is started, and the list of rescaled output data will therefore contain a number of zeros, depending on the point in the basic design routine where the stop occurred. The clearing operation is included to prevent confusion from results left over by a previous design calculation.

(5) METHOD OF OBTAINING CONVERGENCE TO THE DESIRED CHARACTERISTICS

The flow diagram for the computer programme given in Fig. 5 shows that, upon completion of each iteration through the basic design routine, the computed characteristics (iron loss, load loss and reactance) are compared with the desired values. If the permissible tolerance by which these may differ has been exceeded, the adjustable parameters (flux density, current density and core diameter), are modified so that after the next iteration the differences will be reduced, preferably to less than those permitted.

Before the first iteration, the desired characteristics are known namely the iron loss, P_f^d, the load loss, P_l^d, and the reactance, X^d, together with the starting values of the adjustable parameters; namely the flux density, B^{I}, the winding current-density, J^{I}, the core diameter, D^{I}.

After computation of the first iteration the computed characteristics known are: $P_f^{c\mathrm{I}}$, $P_l^{c\mathrm{I}}$ and $X^{c\mathrm{I}}$. If these calculated values are unsatisfactory, the adjustable parameters for the second iteration, B^{II}, J^{II} and D^{II}, must be derived from the known quantities given above.

It may be shown that over a limited range the following equations hold:

$$P_f^{c\mathrm{II}} = P_f^{c\mathrm{I}}\left(\frac{B^{\mathrm{II}}}{B^{\mathrm{I}}}\right)^{f_b} \text{ for } J \text{ and } D \text{ constant} \quad . \quad (2)$$

$$P_f^{c\mathrm{II}} = P_f^{c\mathrm{I}}\left(\frac{J^{\mathrm{II}}}{J^{\mathrm{I}}}\right)^{f_j} \text{ for } B \text{ and } D \text{ constant} \quad . \quad (3)$$

$$P_f^{c\mathrm{II}} = P_f^{c\mathrm{I}}\left(\frac{D^{\mathrm{II}}}{D^{\mathrm{I}}}\right)^{f_d} \text{ for } B \text{ and } J \text{ constant} \quad . \quad (4)$$

and since P_f is dependent only on B, J and D, which are themselves independent, it follows that:

$$P_f^{c\mathrm{II}} = P_f^{c\mathrm{I}}\left(\frac{B^{\mathrm{II}}}{B^{\mathrm{I}}}\right)^{f_b}\left(\frac{J^{\mathrm{II}}}{J^{\mathrm{I}}}\right)^{f_j}\left(\frac{D^{\mathrm{II}}}{D^{\mathrm{I}}}\right)^{f_d} \quad . \quad . \quad . \quad . \quad (5)$$

But it is required that $P_f^{c\mathrm{II}}$ should equal P_f^d; therefore

$$P_f^d = P_f^{c\mathrm{I}}\left(\frac{B^{\mathrm{II}}}{B^{\mathrm{I}}}\right)^{f_b}\left(\frac{J^{\mathrm{II}}}{J^{\mathrm{I}}}\right)^{f_j}\left(\frac{D^{\mathrm{II}}}{D^{\mathrm{I}}}\right)^{f_d} \quad . \quad . \quad . \quad . \quad (6)$$

Similarly

$$P_l^d = P_l^{c\mathrm{I}}\left(\frac{B^{\mathrm{II}}}{B^{\mathrm{I}}}\right)^{l_b}\left(\frac{J^{\mathrm{II}}}{J^{\mathrm{I}}}\right)^{l_j}\left(\frac{D^{\mathrm{II}}}{D^{\mathrm{I}}}\right)^{l_d} \quad . \quad . \quad . \quad . \quad (7)$$

and

$$X^d = X^{c\mathrm{I}}\left(\frac{B^{\mathrm{II}}}{B^{\mathrm{I}}}\right)^{x_b}\left(\frac{J^{\mathrm{II}}}{J^{\mathrm{I}}}\right)^{x_j}\left(\frac{D^{\mathrm{II}}}{D^{\mathrm{I}}}\right)^{x_d} \quad . \quad . \quad . \quad (8)$$

The solution of this set of simultaneous equations for B^{II}, J^{II} and D^{II} gives

$$B^{\mathrm{II}} = B^{\mathrm{I}}\left(\frac{P_f^{c\mathrm{I}}}{P_f^d}\right)^{b_f}\left(\frac{P_l^{c\mathrm{I}}}{P_l^d}\right)^{b_l}\left(\frac{X^{c\mathrm{I}}}{X^d}\right)^{b_x} \quad . \quad . \quad . \quad (9)$$

$$J^{\mathrm{II}} = J^{\mathrm{I}}\left(\frac{P_f^{c\mathrm{I}}}{P_f^d}\right)^{j_f}\left(\frac{P_l^{c\mathrm{I}}}{P_l^d}\right)^{j_l}\left(\frac{X^{c\mathrm{I}}}{X^d}\right)^{j_x} \quad . \quad . \quad . \quad . \quad (10)$$

$$D^{\mathrm{II}} = D^{\mathrm{I}}\left(\frac{P_f^{c\mathrm{I}}}{P_f^d}\right)^{d_f}\left(\frac{P_l^{c\mathrm{I}}}{P_l^d}\right)^{d_l}\left(\frac{X^{c\mathrm{I}}}{X^d}\right)^{d_x} \quad . \quad . \quad . \quad (11)$$

where

$$b_f = \frac{l_d x_j - l_j x_d}{f_b l_j x_d + f_j l_d x_b + f_d l_b x_j - f_b l_d x_j - f_j l_b x_d - f_d l_j x_b} \quad . \quad (12)$$

and the other indices in eqns. (9)–(11) are similar functions of the indices in eqns. (6)–(8).

Thus eqns. (9)–(11) establish the relationships required to modify the adjustable parameters prior to each iteration.

(5.1) Evaluation of Indices

The indices may, in general, be obtained by examination of the changes in the computed characteristics produced by varying one parameter at a time. For example, the iron loss may be calculated from the expression:

$$P_f = W_f \times p \times 10^{-3} \quad . \; . \; . \; . \quad (13)$$

where W_f is the iron weight and p the loss per unit weight of the core material at the working flux density B. Analysis of the relationship between p and B over a limited range of flux density yields:

$$p \propto B^{\eta} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (14)$$

the value of η lying between 2 and 5 according to the type of core material and the mean value of the flux-density range. Since the changes in W_f are negligible for variations in flux density over this limited range, it follows from eqns. (13) and (14) that

$$P_f^{II} = P_f^{I}\left(\frac{B^{II}}{B^{I}}\right)^{\eta} \quad . \; . \; . \; . \; . \; . \quad (15)$$

and it will be seen from eqns. (2) and (15) that

$$f_b = \eta$$

By similar methods the remaining constants may be obtained and the indices of eqns. (9)–(11) may be calculated.

(5.2) Convergence Scheme Tests

To test the performance of the scheme a series of eight designs were computed, with initial values of flux density, current density and core diameter differing by approximately $\pm 20\%$ from the expected final values. The results given in Table 2 show the pronounced variation of iron loss, load loss and reactance computed after the first iteration of each design. However, convergence to within $\pm 1\%$ of the desired characteristics was obtained in every case, with an average of nine iterations per design; for limits of $\pm 2\%$ the average was six. The investigation was based on a 72 MVA transformer, of voltage ratio 13·7/141·6 kV, with an h.v. tapping range of $\pm 10\%$; the core material used was hot-rolled steel. No precautions were taken to assist convergence, current manufacturing standards being used throughout.

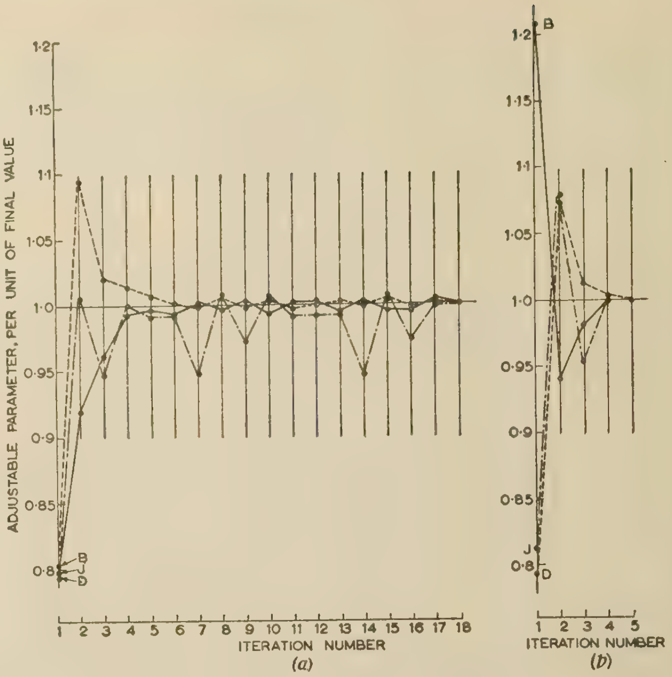

Fig. 6.—Variation of adjustable parameters during convergence tests.

——— Flux density.
—·—·— Current density.
– – – – – Core diameter.

(a) Test No. 1.
(b) Test No. 2.

The variation of the adjustable parameters and computed characteristics for test No. 1, which required the most iterations, are shown in Figs. 6(a) and 7(a), and those for the test with the least iterations (test No. 2) in Figs. 6(b) and 7(b).

Table 2

Results of Convergence Scheme Tests

Test Number	1	2	3	4	5	6	7	8
Starting flux density	10 660	16 020	10 660	16 020	10 650	16 060	10 650	16 060
Starting current density	2·534	2·558	3·787	3·775	2·580	2·515	3·863	3·781
Starting core diameter	653	653	653	653	979	979	979	979
First iteration iron loss	43·49	142·8	43·03	138·8	108·2	362·5	106·5	359·0
First iteration load loss	604·3	382·1	911·1	530·1	296·0	180·4	427·0	265·7
First iteration reactance	89·30	31·19	86·67	25·50	12·28	4·18	10·70	3·83
Final flux density	13 250	13 250	13 300	13 330	13 250	13 300	13 250	13 250
Final current density	3·176	3·150	3·150	3·150	3·150	3·150	3·150	3·150
Final core diameter	822	822	821	820	822	821	822	822
Final iron loss	121·5	121·5	122·6	123·2	121·5	122·6	121·5	121·5
Final load loss	356·0	354·6	354·3	354·0	354·6	354·3	354·6	354·6
Final reactance	13·02	13·01	13·00	12·99	13·01	13·00	13·01	13·01
Number of iterations for $\pm 2\%$ limits	6	4	6	7	7	6	6	4
Number of iterations for $\pm 1\%$ limits	18	5	9	7	8	9	9	9

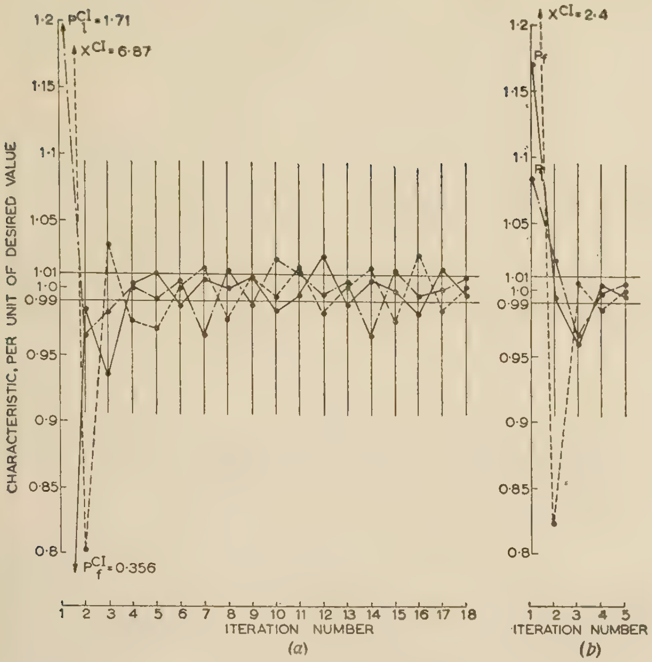

Fig. 7.—Variation of characteristics during convergence tests.

——— Iron loss.
—·—·— Load loss.
- - - - - Reactance.

(a) Test No. 1.
(b) Test No. 2.

To illustrate the satisfactory results obtained with the convergence scheme, the number of iterations required for each of the first 52 designs computed have been arranged in the graphical form shown in Fig. 8. The ranges of output and voltage covered have already been mentioned in the Introduction; the initial values of flux density, current density and core diameter were selected by a competent design engineer.

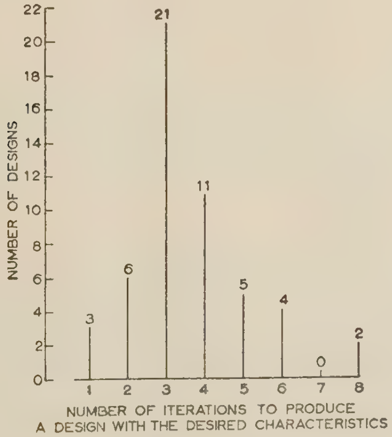

Fig. 8.—Iteration analysis of the first 52 designs calculated.

Design limits ± 2%.
Note similarity to normal distribution curve.

(6) RESULTS OF DESIGN STUDIES

The potentialities of the programme as an aid to the investigation of general transformer problems will be illustrated by results taken from two studies, principally concerned with the minimization of cost.

(6.1) Variation of Current Density Ratio

Fig. 9 shows the variations which occur in the material cost and the copper weights when the ratio of h.v. to l.v. current density changes; comparable results for a 72 MVA transformer with hot-rolled and cold-reduced steel cores are given. All the designs met the same desired characteristics within ±1%.

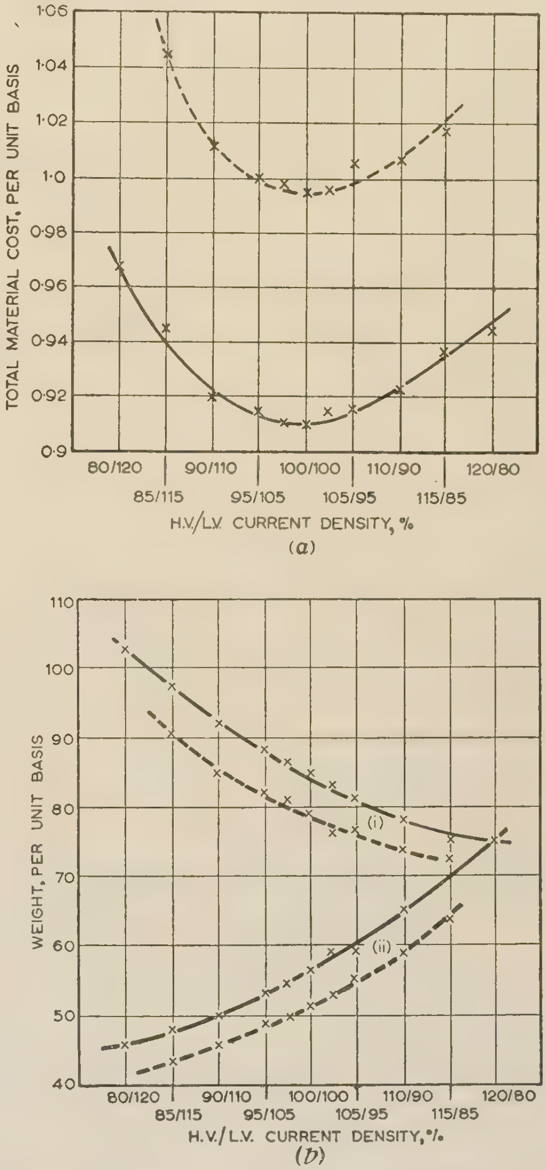

Fig. 9.—Variation of material cost and winding weights with current-density ratio; 72 MVA transformer.

——— Hot-rolled steel.
— — — Cold-reduced steel.
× × × Computed points.

(i) H.V. winding.
(ii) L.V. winding.

To ensure exact agreement between the specified current densities and those actually obtained, the intervals between consecutive conductor stock sizes for both width and depth were made much smaller than usual, but in spite of these precautions, the points obtained did not lie on a smooth curve. The apparent random variations arise from the tolerance of ±1% by which the computed characteristics may differ from those desired. This tolerance was dictated by the uncontrolled

changes which occurred in the computed characteristics owing to rounding the l.v. turns to an integral number, which in this case was approximately 100. However, it is quite clearly shown that, for this size of transformer, minimum material cost is achieved when the current densities are nearly equal.

(6.2) Variation of Window Height

Fig. 10 shows the variation of the iron and copper weights and cost when changes were made to the window height of a 144 MVA transformer with a voltage ratio of 13·7/141·6 kV. As the window height increases the cost initially falls, followed by a rapid rise. The total weight changes more gradually, and also passes through a minimum, although not at the same window height as the cost. This illustrates the difficulty of using the active material most economically when the choice of design is restricted by severe weight limitations. For this investigation seven complete designs were computed, each having characteristics within $\pm 2\%$ of the same desired values.

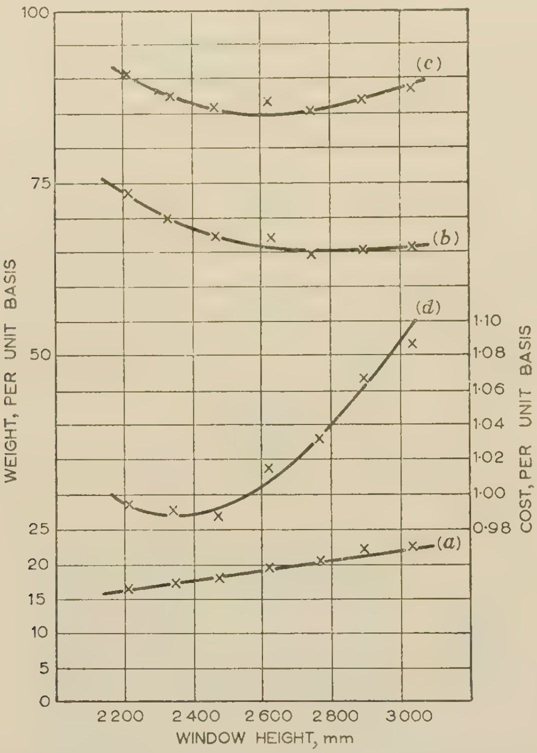

Fig. 10.—Effect of window-height variation, 144 MVA transformer.

(a) Weight of copper.
(b) Weight of iron.
(c) Weight of copper plus iron.
(d) Works cost price.
× × × Computed points.

(6.3) Analysis of Computer Time

The computing time for each iteration through the basic design routine is 22 sec and 5 sec are required for punching the control quantities; 16 sec are required to read in a full list of input data and 35 sec to punch the output data tape. As shown in Fig. 8, four iterations for each satisfactory design is a reasonably conservative estimate, and on this basis the total time required for one complete design is approximately 159 sec. In addition, 3 min 37 sec are occupied by reading in the programme tape; consequently, it is desirable to compute as many designs as possible after the input of the programme.

As an example, the seven designs required for the investigation described in Section 6.2 took approximately 17 min of computing time made up as follows:

	min	*sec*
Input of programme tape	3	37
Input of first set of data		16
Input of 6 sets of changes to data		12
19 iterations through the basic design routine (including time for punching control quantities)	8	33
7 sets of output data	4	5
Total time required	16	43

It will be noticed in the above that the changes to the initial set of input data for subsequent designs required only 2 sec per set, thus effecting a small reduction in computer time.

(7) CONCLUSIONS

The paper has endeavoured to demonstrate the feasibility of programming a digital computer to design large transformers. The computer has produced designs that are at least as satisfactory as those that can be obtained by hand calculation, in a fraction of the time normally required. Extensive design investigations have been completed in a few minutes, with a degree of consistency which previously would have required weeks of laborious calculation.

The logical facilities of the computer have proved most satisfactory in solving problems of considerable logical complexity. The rounding of certain quantities to stock-sizes, which is a feature inherent in all transformer design, has presented no difficulty. The fully-automatic convergence scheme has been shown to be effective, both by the calculation of a large number of routine designs with few iterations per design, and also by a specially devised set of tests. It has been demonstrated that the starting values specified by the designer need only be approximate, owing to the rapidity of convergence. The techniques used in the scheme may be applicable to many problems involving convergence.

A considerable portion of the paper has been devoted to the facilities for the diagnosis of programme failure, and for operator intervention. Although they have rarely been used in practice, it is considered that these facilities should be of interest to all programmers and that a considerable reduction in the time and expense of isolating the cause of a failure may be achieved by their use.

There is considerable scope for improvement of the design method, particularly by the inclusion of sub-routines for precise calculation of reactance, eddy-current loss, impulse-voltage distribution, thermal characteristics and electromagnetic forces. With the aid of a computer it is possible to carry out such analyses on a much more fundamental basis than was hitherto practicable.[6–9] The flexibility of the method of programme control will permit these sub-routines, which are at present being developed, to be incorporated easily as they become available. The programme may be extended to cover a wider range of output and voltage ratings; the extension is limited only by the storage capacity of the computer, and the rapid advances being made in computer techniques suggest that this is very temporary.

The present programme has already proved its value, both in routine design and in the development of designs for new ranges of transformers with economy of time and effort. It is anticipated that further development will lead to considerable changes

in design-office procedure, and will enable designers to make greater use of their creative abilities.

(8) ACKNOWLEDGMENTS

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(10) APPENDICES

(10.1) Derivation of Formula for Covered Conductor Depth

Fig. 11 shows in cross-section one section of a disc-type winding. Cooling from the two vertical surfaces has been

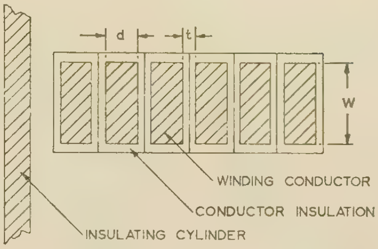

Fig. 11.—Cross-section of disc-winding section.

neglected, since the error thus introduced is negligibly small for the range of transformers covered; this permits the analysis to be based upon one conductor instead of the complete section. Unit length is assumed throughout.

Rate of heat generation per conductor .. $= \dfrac{\rho I^2(1+e)}{dw}$

Horizontal surface area from which heat will be dissipated .. .. $= 2k(d+t)$

Therefore dissipation, $q = \dfrac{\rho I^2(1+e)}{2(d+t)kdw}$

But $J = \dfrac{I}{dw}$

Therefore, covered conductor depth, $(d+t) = \dfrac{\rho IJ(1+e)}{2qk}$

(10.2) Preliminary Tests on Design Sub-Routines

An advantage of the division of the basic design routine into sub-routines is that each may be comprehensively tested in isolation before it is incorporated in the complete programme. Owing to the presence of branch points, most sub-routines must be tested with more than one set of test data, and in order to minimize development time on the computer, a special testing technique has been used. A test programme has been written which may carry out up to 80 tests in succession on a group of sub-routines. A set of input data must be prepared for each test.

A predetermined number of results are printed for each test before the next is started. The overflow indicator is cleared before each test, and in the event of overflow during a test, the results will be preceded by a special symbol and the reference number of the sub-routine. Operator intervention is necessary only if a programmed stop is encountered, or if the computation continually loops round a group of orders. In either event, two orders are inserted via the hand-switches, to cause printing of the data in the computing store; afterwards, the computer automatically proceeds to the next test. This method of testing has been found most effective, as the results can be examined away from the computer; 'single-shot' testing, i.e. causing the computer to obey orders singly under operator control, has rarely been used.

DISCUSSION BEFORE THE INSTITUTION, 28TH NOVEMBER, 1957

Mr. H. M. Lacey: My comments are concerned mainly with the limitations of the machine, for even technical people are sometimes apt to forget that a machine can give out only what has been put in. It is true that, through the ingenuity of its maker, it can apply mathematical processes to the information it is given, but it cannot devise new methods of calculation, distinguish between correct and incorrect information, or give a considered opinion on the overall merits of the final design. The experienced designer, on the other hand, tends to develop a kind of sixth sense which draws his attention to features which, while conforming to the basic requirements, can produce undesirable results under abnormal conditions of operation.

Many examples could be cited. In order to ensure satisfactory thermal conditions the machine is provided with information on current density, type of spacers, conductor insulation, eddy-current loss, etc. Only an experienced designer can say whether all this information is consistent, and even he needs to have the full design details before he can give a final opinion.

For example, the conductor dimensions and the leakage flux density must be known before the eddy-current loss can be estimated. For the machine it would require an involved calculation, although the designer might be able to make an inspired guess. Similarly, the depth of winding must be known before it can be decided whether the initial information is reasonable.

Another example concerns mechanical forces, an accurate estimate of which involves a very complicated calculation. The machine could be used for this calculation, but hardly as part of the routine design programme. For this aspect, the designer's knowledge of features to avoid would be more useful than speed and accuracy in calculating forces in a design which, from this point of view, might be basically unsound, e.g. with regard to such features as tapping arrangements.

A third example relates to reasonable immunity from the effects of surges. A great deal of research has been devoted to this subject, but it is very doubtful whether the machine could produce any really useful result from the kind of information with which it could be fed. The experienced designer, however, knows the good and bad features of design from this point of view and designs accordingly. His knowledge is the cumulative result of theoretical study, test results and operating experience.

So far, my remarks may appear to be entirely derogatory, but this is not my intention. The value of the machine may be appreciated, as well as its limitations, although its superiority over the slide-rule may be partially offset by lack of discrimination. There is no doubt that it is an immense advantage to be able to ascertain in a few minutes the effect of varying one or more parameters, but the machine is no substitute for the skilled designer. In this connection I prefer the title of Reference 6—'The digital computer *as an aid* to the electrical design engineer'.

Finally I would comment on the opening paragraph of Section 7, in which reference is made to 'weeks of laborious calculation'. None of my experience as a designer could be so described, and I doubt whether design or designers have radically changed, in spite of all the complications which have been introduced. To do all that the machine does might entail 'laborious calculation', but the good designer will save himself most of it by making a good first guess.

Mr. E. T. Norris: To appreciate the role of the computer it is important to distinguish clearly between design and calculation. The art of design includes, first, the choice of suitable substances (having regard to their mechanical, electrical and thermal characteristics) for all the various materials used in a transformer; secondly, the choice of suitable stresses (again mechanical electrical and thermal) for all these materials; thirdly, the consideration of each stress under both working and test conditions and also in certain abnormal conditions such as surges and short-circuits; fourthly, the derivation of practical engineering formulae for calculating values of all these stresses and for determining the electromagnetic characteristics of the transformer. This is the art of design and the engineering skill of the designer.

The rest, namely calculation, is purely numerical and consists in calculating values for all the design characteristics, repeating the process by trial and error until a combination has been achieved which satisfies the specification requirements while meeting all of the stress limitations. This work could be done by non-technical assistants were it not that, making blind guesses at the various values, the number of trials and errors—iterations is the modern word—would be so great as to be beyond the limits of human fatigue. The computer knows no such limits, and in saving the designer the mental drudgery of this work, it is the greatest boon in the design office since the slide-rule. Fortunately, everyone can afford a slide-rule.

The usual examples of computer application, including those in the paper, are artificial in that a prearranged specification (foreknown to be capable of good design) is fed into the computer initially so that it merely has to reproduce the anticipated numerical answer.

Suppose in one example the required losses were halved. A design would not be possible and presumably the computer would struggle along with continued iterations until bedtime. Does not this show that the number of iterations, as for example in Figs. 7 and 8, is not determined merely by the convergence characteristic of the computer, or even by the accuracy of the designer's initial guess, but mainly by the 'tightness' of the specification?

If, on the other hand, the losses were doubled, many different designs would be possible and the computer should produce one of these alternatives with very few iterations. If the process were repeated, would it produce the same or another alternative?

Mr. G. N. Leech: One of the basic problems at present affecting manufacturers of electrical machinery is how to meet an ever-increasing demand for their products. Demand is doubling every ten years, but it is very unlikely that design staff will increase substantially in numbers in the foreseeable future. Obviously, as in other fields where there is a shortage of man-power, one turns to mechanization, and the digital computer seems to be a promising tool in the field of transformer design calculations.

At present, there is no indication that its use will lead to any radical change in the design of transformers. However, the speed with which the effect of varying the design parameters can be computed enables the designer to investigate a much wider range of possibilities than would be practicable with slide-rule computation. This is particularly helpful when investigating projects outside the range of past experience.

Mr. R. E. Buxton: The authors mention that the programme described is being extended to cover a much wider range of designs with a greater generality of treatment. The particular limitations obtaining within each band of ratings over this extended range give rise to problems whose solution requires an approach differing in detail, but significant detail, from that discussed in the paper. For example, in the routine design of distribution and medium-power transformers it is common practice to employ standard frames, where, for any given frame, the core diameter and limb centres are fixed while the window height is varied in regular steps between prescribed limits. Such an arrangement permits the use of stock parts and drawings in the production of a standardized range of units, and I should like to discuss some of the differences and their effects when applying the computer to design on this basis.

The programme in its present form is not entirely suitable for this purpose, for two reasons. First, with relatively large intervals between available standard core diameters it is clearly impossible in the general case to converge to within close limits of all the desired characteristics. Secondly, where there are no severe weight or transport limitations—and this is generally the case with these smaller units—selection of the most suitable window height becomes extremely difficult. These problems can be resolved by adopting a slightly different design technique and modifying the convergence scheme to suit. In direct contrast to the existing procedure, core diameter is made a preset parameter and window height one of the three adjustable parameters, so that for any standard core diameter the most appropriate window height is automatically computed. In practice, the interval between permissible window heights is rounded off to some convenient stock size, so that to maintain convergence within consistently close limits it becomes necessary to adjust

an additional parameter of the design, and in our work provision has been made for varying the reactance gap.

Thus the computer has available a range of standard frame dimensions and strives to arrive at a satisfactory design using only those values; where necessary—for final convergence within the limits specified—suitable automatic adjustment is made to the reactance gap.

Mr. F. W. Gee: In the course of development work to find the best programmes, and in doing design calculations (not designing), we found that it is the experienced designer who must produce the programme. A transformer engineer can learn enough about the computer in 10 days to start programming, but it would take considerably longer to teach a computer expert enough about transformer engineering. It is only when the experience of a designer is put into the programme that there is any hope of success, which emphasizes that the computer is merely a tool, rather better than the slide-rule but rather less intelligent than the office boy.

The programme discussed in the paper has been developed by making certain simplifying assumptions to get a programme that will work.

Section 7 mentions scope for improvement; there has already been some progress in introducing into the programme calculations for certain values that are at present assumed. We started with a more detailed programme, and worked out some of the things which are assumed in the paper. Experience gained by the use of that programme then enabled it to be simplified for limited ranges of transformer. Conversely, the authors started with a simplified programme and added complications. In a complete attack on the design problem there will always be more than one type of programme in use. In one case we want the optimum design to meet certain conditions, e.g. balancing the cost of losses against the first cost of transformers; in another these considerations are past history, and we must produce the cheapest design to given guarantees. Programming will therefore never be static, even if we omit the changes in the real design.

We may reach the stage where the programme is put into the hands of the consumer and he is told just to put in certain parameters. He works out the programme, gets the cost, adds $x\%$ profit for some manufacturer and another 2% for out-of-work designers, and chooses a manufacturer to make a design to those instructions. This is not a vision of the future at all, because the computer is merely a labour-saving device and is neither intended, nor claimed, to design transformers.

Mr. E. R. Hartill: The Americans have published several papers on transformer design by computer, and they seem to be putting more effort into the subject than we are in England. The present authors have, however, gone into it in more detail, and done quite a lot of essential development work. Would they comment on the American claim to be doing complete transformer designs by computer? This would presumably include all the tap position and conductor transposition diagrams, etc., which at present have to be done by hand. I should like to know how much time is actually spent on the computer compared with the total time still required to complete a design, including the diagrams, preparation of the data tape, and time involved in travelling to the computer centre.

The authors say that it requires 17 min to complete the design calculations, which would cost £10 at current rates. One of the 'tail' programmes mentioned concerns the calculation of impulse-voltage distribution. We have developed this method,* which takes about 2 hours for a complete run on the computer and costs about £80. The cost of computation is therefore quite high; in fact, surprisingly little can be done for £1 000. Computer breakdowns and travelling time add to the expense. In our experience, this present high cost is a barrier to the more widespread use of the computer for engineering calculations. Engineering structures can be designed without a computer and using only simple fundamental formulae. The designer will not be prepared to pay too high a price for more refined calculations which may change the basic design only slightly.

Mr. A. R. Telford: One of the main troubles we have had in writing a transformer design programme has been to cause the computer to design around existing sizes of cores and cylinders.

Mr. Buxton referred to the problem in distribution transformer design, but it becomes worse the larger we go, because for distribution transformers and transformers up to about 10 MVA there are plenty of standard cores in $\frac{1}{4}$ in steps and plenty of cylinders in $\frac{1}{8}$ in steps, up to about 20 in. Up to 40 in diameter they go in 1 in steps, and above that, where the manufacturers like to put them. In the region covered by the authors' programme they are very few indeed. Although it is theoretically possible to pack an existing mandrel to any size, it is not always economic.

We are still seeking a satisfactory way to make a computed design take full account of existing sizes, particularly of cylinders. I should be interested to know whether the authors have done anything about it.

It takes years of experience to know where to put the taps, how to arrange them and how to get them out. To avoid the obvious difficulties of programming this, we compute several approximate designs on several standard core sizes, take what looks like being the best and finalize it by hand. At the present stage of transformer programmes this is perhaps a more economical way of doing the job, and produces a lot less trouble unless the programme is extremely good.

Mr. K. S. Rowe: In the range of transformers to which the paper refers the losses are not always known at the quotation stage, and therefore a different method of convergence is required to arrive at the optimum quotation design. We have made provision for this in our own programme.

The convergence routine described in the paper has been simplified by assuming the eddy-current loss to be a constant proportion of the I^2R loss. In practice, the eddy-current loss varies with flux density, core diameter and current density, and some cases can be a dominating factor in the final selection of core dimensions; it can also limit the strand size of the winding. Therefore the routine described in Fig. 4 would have to be modified for a change in eddy-current loss. The curves shown in Fig. 9(*a*) are true only for equal eddy-current losses in both windings, although the effect of different losses in the two windings does not alter the overall picture very much.

I should like to ask the authors two questions about eqn. (8). It appears as if the indices xb, xj and xd have been derived by keeping the clearance between the high- and low-voltage windings fixed. If so, does this mean that different sets of indices must be used for different voltage classes? Also, does the programme allow for the fact that the h.v.-l.v. clearance required might be larger than the minimum value in cases where a relatively high reactance is required?

Some useful information was obtained as a result of some 80 alternatives of a 10 MVA design produced on the computer referred to by the authors, using our programme. Fig. A(i) shows how the iron weight varies with flux density when the reactance and copper loss are constant. The broken curve has been derived in a manner similar to that used for Fig. 10, i.e. choosing the correct window height, and is useful for selecting the optimum core area for a given flux density. Fig. A(ii) shows how the iron

* Dent, B. M., Hartill, E. R., and Miles, J. G.: 'A Method of Analysis of Transformer Impulse Voltage Distribution using a Digital Computer', *Proceedings I.E.E.*, Paper No. 2452 S, December, 1957 (105 A).

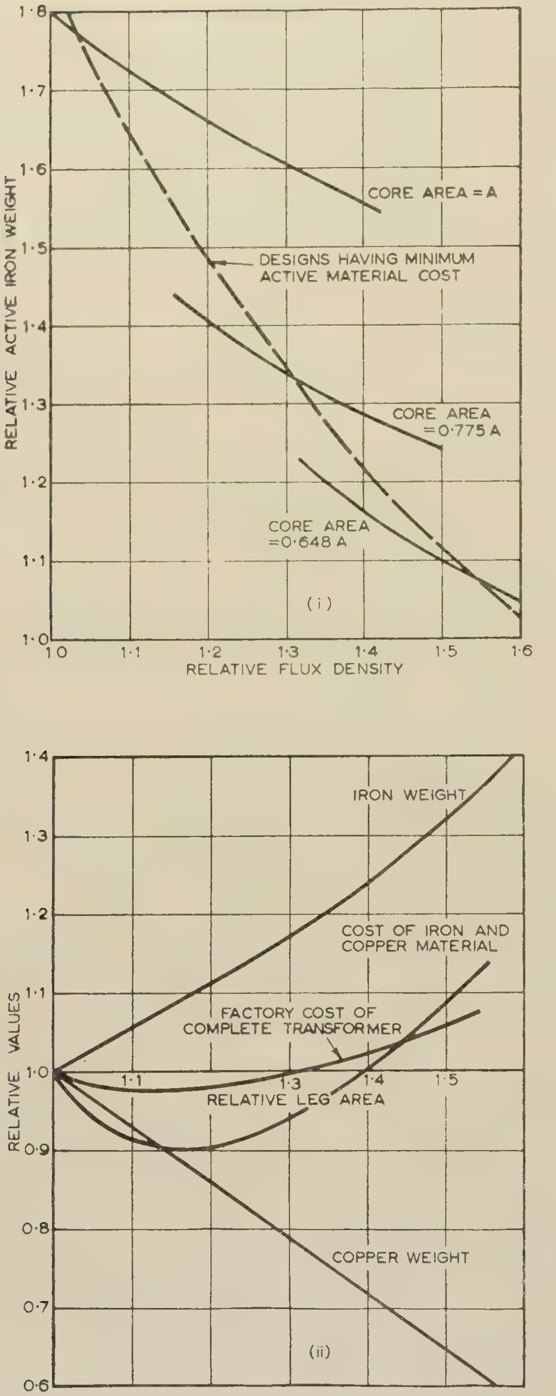

Fig. A.—Some design parameters for a 10 MVA 33/11 kV transformer with a tapping range from +5% to −15% and a tertiary winding.

(i) Variation of iron weight with flux density.
(ii) Variation of iron weight, copper weight and cost with core area.

weight, copper weight and cost vary with core area. The conclusion drawn is that, if the flux density is fixed, the total cost varies by only $\pm 2\frac{1}{2}\%$ over a wide range of core area.

Mr. H. McGregor Ross: The majority of programmes written for computers are for specific calculations, but the distinguishing feature of the type of work described in the paper is that the machine is used as an adjunct to design work. In practice, the programmes for this work are more difficult to write than are the others, and for each design programme there are probably 100 of the others.

The paper shows how the machine may be used to improve upon a very rough approximation to the required design conditions by a process of iteration; it is one of the few papers which adequately illustrates this process, and it also shows how rapidly iterations settle down to an adequately accurate solution.

Another typical aspect of computers is that they function quickly enough to permit the design operation to be repeated many times with differing values of some parameter. In this way it becomes possible to plot the effects of changes in any given parameter. Figs. 9 and 10 show this very clearly.

We have found in the general use of these machines that processes akin to those described can result in a small but significant improvement in some feature of the design or of the system as a whole. It is usually possible to obtain from 1 to 3% improvement in some desired characteristic. And since this desired characteristic may represent a saving in one of the raw materials, or the total cost, this can be of great importance.

Mr. J. E. L. Robinson: Having made some study of the economics of purchasing a computer for machine design, I would emphasize for the benefit of others so placed some six main advantages, namely

(*a*) One rapidly accumulates a much more extensive and complete background to design experience.
(*b*) It becomes possible in the working out of every design to include exact solutions of sub-calculations which have previously been jumped.
(*c*) The advantage of new advances in design techniques or increased stressing of materials can be more quickly considered and exploited in current designs.
(*d*) Within an existing design framework a computer frequently arrives at a slightly cheaper solution than the designer, because it is prepared to complete the circuit of calculations a few more times.
(*e*) Because it becomes possible to complete detailed designs before the tendering stage, the likelihood of optimistic costly mistakes can be reduced.
(*f*) A considerable saving in designers' time releases them for other problems.

It is difficult to predict a monetary value for the first three items, but some consideration and study enables an annual value to be placed on the last three. By using the computer to reconsider a range of transformers which had previously been designed and built in the ordinary way, we calculated that $\frac{1}{2}\%$ reduction in cost is a conservative estimate for the average contribution of item (*d*). I am not keen to give details for item (*e*), but after reviewing the difference between past tendering-stage-design-cost estimates and final design estimates, we calculated that it was a substantial amount. For the item (*f*), 20% is probably a conservative estimate.

Mr. B. J. Chalmers: The authors have shown how the use of three simple equations enables them to effect convergence to the required design. Will they extend this and indicate whether they maintain that similar relationships may always be deduced in any other problem of the same nature? How, in general, may these relationships be determined, and will they always necessarily give the convergence required?

For example, we may have a problem in which we recognize, say, five independent variables and perhaps three required quantities to be obtained within specific tolerances. Do the authors maintain that the same sort of approach could be applied, bearing in mind that the relationships between the five independent variables and three dependent variables, say X, Y and Z, might not be expressed by simple equations? X may be a quantity which is not a continuous function, and may have only a limited number of possible values; Y may not be related by simple equations either, and its value may be

determined only by an iterative calculation; Z could be another quantity which is dependent upon all five independent variables.

The question, then, is how to determine laws by which to adjust the five independent variables in order to obtain values of X, Y and Z within specified tolerances of the particular figures required. Experience in the particular problem may indicate the types of law which are most likely to give the required effect, but two points should be noted here. First, this method does not necessarily give the best or only result; secondly, it is not to be assumed that it will produce convergence—it may actually cause divergence or oscillation.

Mr. B. M. Bird: It has been said that the digital computer cannot compete with the shrewdness of a designer. To a large extent a designer's shrewdness is used to avoid carrying out long and tedious calculations. However, because of the computer's ability to calculate at such tremendous speeds, it can work through a far more lengthy calculation than the design engineer and still arrive at the solution in a fraction of the time taken by him. I believe that in this respect the digital computer can in some measure compensate for its lack of shrewdness.

The possible difficulties involved when the increments in the available core sizes are not constant has been mentioned. I am working on rotating-machine design calculations, where the increments in the frame sizes available are by no means constant, and have found that this presents no difficulty provided that sufficient storage space is available in the computer.

I question the value of printing out some of the data relating to each intermediate design as it is completed. I believe that, although this might be useful while developing the programme, it is inadvisable to continue the practice in the production programme. It must be remembered that the computer is unable to compute and print simultaneously, and thus any unnecessary printing should be avoided.

I would also suggest that the final design calculation should be presented in a form which is more familiar to a transformer designer. At present the information is presented in a long list of numbers which must have the corresponding descriptions written against them. I feel sure the transformer designer would find the information more easily digestible if the figures were presented in some disposition familiar to him and perhaps on a preprinted form. This is often done in work involving routine calculations such as pay-roll computation.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. W. A. Sharpley and J. V. Oldfield (*in reply*): In drawing attention to the machine's limitations, Mr. Lacey underestimates its capabilities. The difficulties mentioned may be overcome by fulfilling the following three conditions: first, the input data must be sufficiently comprehensive to ensure that adequate information is available during computation; second, the programme must be written to follow exactly the process adopted in hand design (this implies that the logical foundation of all the decisions made during hand calculation must be clearly identified and included in the programme); third, that separate sub-routines are written for each major variation in any part of the complete design programme, e.g. different winding types (disc, crossover, layer, etc.), would have separate sub-routines. Thus the designer's skill in selecting a suitable arrangement may be combined with the computer's speed to obtain satisfactory designs very quickly. A later stage would include in the programme the logic to select the suitable arrangement. Guesswork, however inspired, is not, we feel, an essential step in transformer design, but is used to fill the gaps in the existing knowledge of the physical phenomena concerned.

It was not our intention to imply that normal design requires 'weeks of laborious calculation', but that investigation of certain problems, e.g. the optimum current-density ratio between windings, requires many designs all meeting the specified characteristics within close limits—say $\pm 1\%$—necessitating much laborious work. Published mathematical solutions drastically simplify the problem, making the conclusions of doubtful value.

We thank Mr. Norris for his concise definition of the 'art of design and the engineering skill of the designer', but we disagree that the rest is 'purely numerical'. It is a process of repeated cycles of calculation, inspection of results followed by a decision upon which course to follow next. The computer programme would at all stages follow the designer's course, whereas the non-technical assistant would be lost in the maze of guesswork.

If the computer were caused to attempt a design with half the normal losses, which by hand was impossible, either a number or a dimension would exceed its scale factor or compliance with one of the tests to ensure a satisfactory result would be impossible. In either case computation would cease, probably within a few minutes. With twice normal losses many designs may be satisfactory, but it is possible to programme the computer to select the best from some specified criterion, e.g. cost, minimum total weight, etc. Repetition would produce the same design.

We also have found it desirable, as has Mr. Gee, for a designer to write the programme. Mr. Gee's approach, by simplifying an initially very comprehensive system, is certainly different from ours but very useful in assessing the suitability of any one computer.

We regret that we are unable to give Mr. Hartill an accurate assessment of the scope of American programmes owing to lack of detail in the published accounts. Their use of the largest and fastest computers indicates the extent of their effort. The programme for detailed impulse-voltage calculation is of great interest, and we anticipate that improved simpler formulae for routine design will be obtained. Our computing time is small compared with that for hand completion of full shop instructions; an exact figure is made difficult to estimate by the variety of designs computed.

Mr. Telford mentions difficulties arising from cylinder-size restrictions. Within our programmed range we consider that it is economically justifiable to pack existing mandrils to any required size.

As Mr. Rowe suggests, the indices were obtained with constant clearance between windings, although one set has proved adequate for variations up to 3 : 1. With the present-day ratio of copper to iron price, it appears uneconomic to obtain high reactance by increasing the interwinding gap. Figs. A(i) and A(ii) would be even more interesting if the computed points had been included, for we find that departures from a smooth curve are caused by integral number of turns and stock conductor size restrictions. It is not stated whether the h.v. to l.v. winding clearance has been kept constant during these runs; the value of the results will be reduced if the clearance has been varied.

Extension of our convergence scheme to handle Mr. Chalmers's problem should be possible, assuming reasonable continuity of the *independent* variables, although two additional dependent variables may be required to achieve a unique solution from five independent variables. The relationships may be obtained either by the method proposed in Section 5.1 or by analysis of the results obtained when each independent variable is altered in turn. The continuity of X, Y and Z is unimportant as intermediate values calculated during convergence need not be physically permissible.

We agree with Mr. Bird that design data displayed on a printed form would be most convenient, but the alignment of many columns would require greater output time.

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NORTH STAFFORDSHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By H. A. P. CADDELL, M.A., Member

'FACTORS AFFECTING THE EFFICIENCY OF THE RETAIL DISTRIBUTION OF ELECTRICITY'

(ABSTRACT *of Address delivered at* STOKE-ON-TRENT 14*th October*, 1957.)

The overall cost of distribution per unit sold in England and Wales fell from 0·81d. in 1921 to 0·43d. in 1956; it increased, however, from 0·42d. in 1948.

The costs of distribution are examined in detail and it is concluded that, while increased sales make a contribution to a reduction in costs per unit sold, these will be substantially reduced by an increase in units sold per pound of capital expenditure, which bear on some 60% of the costs of distribution.

Equally important considerations are the efficiency of performance of the tasks of distribution and the price at which bulk supply is purchased.

The Performance of the Tasks of Distribution.—The majority of these are of a routine nature, and management cannot escape responsibility for meticulous and sustained attention to detail in organization, procedures and selection of materials.

Many of these routine tasks are performed by individuals working alone in the field remote from supervision. Consequently the attitude of the employee to the undertaking is important, and in general is found to be a responsible one. Incentive schemes might well be fruitful, although care has to be taken to ensure that too great an emphasis on payment by results does not detract from this responsible attitude.

A weighty factor is the attitude of mind informing the industry and its structure. The operating units should be commands that are informed by the standards and objectives set by top management and are at the same time trusted and independent.

Between 1951 and 1956 equivalent man-hours for operating and maintaining the system and for administration, both per £100 of capital expenditure, fell by 27% and 37% respectively, and for meter reading and billing per consumer, by 22%. Productivity has therefore increased.

The Price at which Electricity is Purchased in Bulk.—The shapes of the estimated load curves for industrial, domestic and commercial consumers are studied. The three main classes of load are broadly complementary to each other in summer and winter. There remains, however, the critical time between 8 a.m. and 9 a.m. when the industrial and domestic loads are subject to rapid change. The domestic load reaches its maximum and starts to decline earlier than the industrial load. Near coincidence is considered to be inevitable with our present social habits, whatever the state of development of the industrial and domestic loads. In this period the factory operative is at work, while there is still intense activity in the homes, where there are office and shop workers and schoolchildren. High national investment in atomic generation may force an adjustment of factory, office and school hours.

The industry has to develop 'valley' and high load-factor loads. Pottery firing kilns run at annual load factors of 70 to 80%; the performances of various types of electric kilns are detailed.

Units Sold per Pound of Distribution Capital.—Units sold per annum per pound of distribution capital increased from 46 in 1921 to 73 in 1956.

Mr. Caddell is with the Midlands Electricity Board.

These figures can be increased (*a*) by increasing the individual load factor on each part of the system, (*b*) by loading all parts to capacity, (*c*) by the distribution design being the most economical for a given purpose, and (*d*) by the greatest development of load because the capital cost per kilowatt of distribution plant decreases with increasing size.

Considerations (*b*), (*c*) and (*d*) are dealt with under 'Distribution Design'.

Distribution Load Factor.—It might be expected for domestic consumers that the load factor at a local transformer would be higher for the more highly developed loads, measured by the average connected load per consumer.

For about 30 groups, each of about 100 consumers, a.d.m.d. and consumption are plotted against connected load, all per consumer. Both indicate a straight-line relationship, and the annual load factor for the whole is 29·5%. It is concluded that increased development is not necessarily accompanied by an improvement in load factor.

These tests were made about 10 years ago. Over the intervening years, changes in relative fuel prices might be expected to have caused an improvement in load factor for the same connected load per consumer. A consumer with a connected load of 5 kW now has an a.d.m.d. of 0·83 kW and uses 2 100 kWh a year, compared with 0·57 kW and 1 400 kWh. The straight-line relationship is still evident, and the load factor of the whole is unchanged at 29·5%.

From further tests there is little doubt that the average cooker and water-heater load factors related to system peak are above that of the system as a whole. While the cooker has a rather low load factor on local plant, that of the water heater is probably above the average figure of 29·5%. It is therefore very desirable to increase the cooker and water-heater loads.

Typical saturations of the main domestic appliances in 1945 and 1955 are shown. The increase in cooker saturation is small. Water-heater saturation is still very low. The increase in space-heating load is relatively small.

Load factor can be substantially increased by storage space-heating, and daily load curves for all-electric flats equipped with electric floor-heating are shown.

Industrial and commercial loads are also considered.

Distribution Design: Primary Systems.—The first consideration is to give security of supply by providing firm capacity equal to the load. Firm capacity is regarded as the capacity remaining when the largest unit is unavailable. Under these conditions transformers and cables are expected to carry 30% above continuous ratings.

Within this framework it is generally necessary to prepare several alternative schemes. The choice will depend on annual costs and on life before further reinforcement is necessary.

11 kV/M.V. Urban Distribution.—The considerations are voltage drop, security of supply and maintenance facilities. Because of load factor and the volume of copper required to deal with voltage drop, losses are a secondary consideration on m.v. networks. Automatic voltage regulation at 33/11 kV sub-

stations and line-drop compensation up to 4% should eliminate 11 kV voltage drop. M.V. distribution should be designed for a voltage drop of 4% on balanced load.

The amount of unbalance varies inversely with the number of consumers. It may be necessary to allow a voltage drop, due to unbalance, of one and a half times to twice that for balanced load. Close attention to balance is important.

From the typical shape of housing development a formula can be adduced relating average cross-section of distributor to area covered, total load, number of substations and permissible voltage drop, and from this the minimum total cost condition can be calculated.

On this basis the capital costs of a square mile of housing development are calculated for 1, 2, 3 and 4 kW loads per consumer at £22, £28, £32 and £36 per house respectively, excluding h.v. system and services. This confirms lower capital costs per kilowatt for higher loadings and emphasizes the necessity of realistic load estimates. The corresponding units sold per pound of this capital expenditure range from 117 to 294.

There is bound to be conflict between the necessities to load all plant to capacity and to ensure optimum design at the higher stages of development. These must be harmonized to the greatest degree.

This is illustrated by considering a square mile of housing development and assuming a load of 1 kW per consumer for the first 10 years, 2 kW for the second 10 years and 3 kW for the third. If initially distributors and substations are laid out for 1 kW per consumer and both are reinforced subsequently, the total costs over the 30 years are about £754 000. If the distributors are laid out initially for 3 kW per consumer and the substations for 1 kW, only the substations being reinforced subsequently, the total costs are about £554 000. A good compromise is to lay out the distributors initially for 2 kW per consumer and thereafter to reinforce only the substations. This gives total costs of about £529 000, while the annual costs at the 3 kW stage are only about £3 000 more than in the previous case.

As to security of supply, the incidence of failure of m.v. cables has been stated to be about 2 per 100 mile-years, of h.v. cables about 6 per 100 mile-years, and of distribution transformers about 0·3 per 100 transformer-years.

The individual m.v. consumer is unlikely to suffer interruption within a lifetime due to the few hundred yards of m.v. cable and the local transformer with which his supply is associated. Alternative supply to cover these contingencies is unnecessary. For h.v. cables the incidence of failure is higher and the length of cable associated with the individual m.v. consumer is greater. A cable failure of this type is likely to take up to 24 hours to locate and repair.

Alternative h.v. supply is, in any case, necessary for substation maintenance. A reasonable compromise is to provide alternative supply to every other substation, with m.v. interconnections to adjacent substations equivalent to about one-third of the maximum load. This gives adequate maintenance facilities, and the extreme consequence of h.v. cable failure is restriction of load, if the failure occurs at a period of heavy load.

The cost of services—about £15 per house—can be reduced by laying distributors in gardens close to the houses, and the low fault incidence of m.v. cables indicates that this is unlikely to lead to difficulties.

Rural H.V./M.V. Systems.—Voltage regulation up to 6% has to be allowed in the h.v. system, even with maximum line-drop compensation, and present tendencies are to limit the length of m.v. distributors to the absolute minimum. The problem is to develop the most economical overhead-line design and construction methods. High-speed auto-reclosers reduce fault incidence to a figure comparable with that of underground systems.

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ELECTRIC CONTROL OF STAGE AND TELEVISION LIGHTING

By F. P. BENTHAM.

(*The paper was first received* 21*st March, and in revised form* 15*th July*, 1957. *It was published in November*, 1957, *and was read before a joint meeting of the* Utilization Section *and the* Radio and Telecommunication Section 12*th December*, 1957.)

SUMMARY

The paper surveys the progress in switchboard control of stage and television lighting which has been made in the past 25 years. The various types of dimmer which form the basis are outlined, with particular reference to their remote control. The methods of co-ordinating control, using particular forms of levers and grouping aids, such as master selection and presetting, are described.

Details of the application of organ-console techniques to the 'playing' of light are given, together with reasons for a preference for electromechanical dimmer systems rather than the American all-electric dimmer or the Continental electro-mechanical desk. All three systems are described.

(1) INTRODUCTION

A stage-lighting installation is fed via a switchboard, the control of which—preferably in the hands of one man—must weld circuits and lanterns into an instrument of artistic expression. The more nearly the control approaches an instrument that is played rather than a switchboard to be worked, the more satisfactory the welding will be. Such an instrument may have more than a hundred dimmers, yet their electrical form should exercise only a secondary influence. Stage lighting involves slow, fast or instantaneous changes in the light output from the lamps forming various groups, and such changes often follow each other in rapid succession. The problem lies in the control of the controls. Latterly, television lighting control has tended to present a rather similar problem; but whereas in the theatre there is a large fund of operational experience—verging on tradition—on which to build, in television nothing can be taken as settled or definitive. Architects may design and build concrete studios, but within them the equipment and production techniques are in a state of flux. It therefore follows that the paper is mature and considered in respect of the theatre, but must be ephemeral and speculative in its approach to television.

(2) DIMMERS

The dimmer is the characteristic feature of each individual circuit for stage lighting and to a lesser extent for television lighting. Tungsten-filament lamps form the basic illumination, and a dimmer must regulate their intensity by lowering the voltage progressively until the filament just glows. This point will occur at about 12% of the line voltage and the current in the circuit will be approximately one-third of its full-load value. The voltage/light-output characteristic [Fig. 1(*a*)] shows that, where dimming is achieved by comparatively coarse tappings, the steps must be graded if flicker is to be avoided.

(2.1) Resistance

Originally, banks of simple liquid dimmers were the rule, the moving electrodes being operated by tracker wire from handwheels in some remote position. A few of these installations

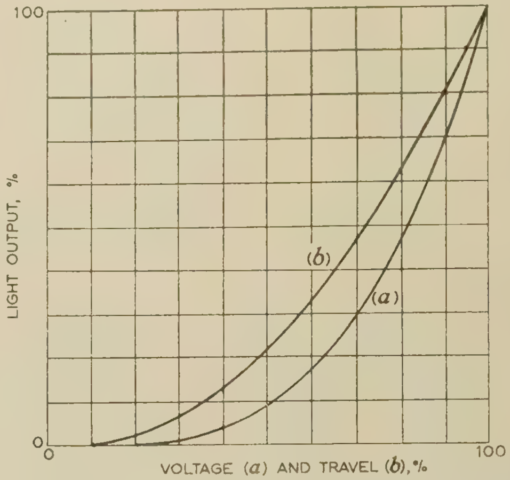

Fig. 1.—Variation of light output with auto-transformer setting.
(*a*) Linear auto-transformer.
(*b*) Stage-dimmer auto-transformer.

still remain, and that in the Drury Lane Theatre, commissioned in 1902, went out of service only in 1950. Wire-wound resistors followed these, and the large majority of dimmers made in Britain to-day still take this form. The reason is their low initial cost, which is essential for small halls, schools and 'little' theatres, but their use may be advisable in large theatres and television studios to allow a greater proportion of expenditure to be allocated to the control proper.

The cheapest form of resistance dimmer consists of two parallel slates wound with four gauges of wire, butt-welded into a single length at the time of winding. The two windings are bridged by a sliding contact and the whole is fitted with a cover and a scale. This form is inconvenient for more than a few circuits, owing to the difficulty of collective operation, and stud contacts are preferable. These are mounted radially in two parallel arcs, and a pair of copper-carbon brushes, sprung apart, bridges the two tracks. There are 100 steps (50 studs per track), ranging from short-circuit to open-circuit of the resistance. Each top step has 0·9% of the total resistance, and each bottom step has 9%; graduation of the steps is often arranged so that a 50% load can be dimmed right out (Fig. 2), but this is not advisable for lamps below 250 watts rating. Television can permit 1% light at the bottom end, thereby extending the possible variable range down to 25%.

(2.2) Auto-Transformer

In the United States, several mass-produced auto-transformers, virtually interchangeable for size with the resistance plates, are used. In England, because of the lack of a transformer which will mount so conveniently, a special unit has recently been devised on a pair of the standard die-cast resistance-dimmer frames; it is a compromise, but the drawback of a clumsy iron circuit is outweighed by its mechanical-drive advantages.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.
Mr. Bentham is with the Strand Electric and Engineering Co., Ltd.

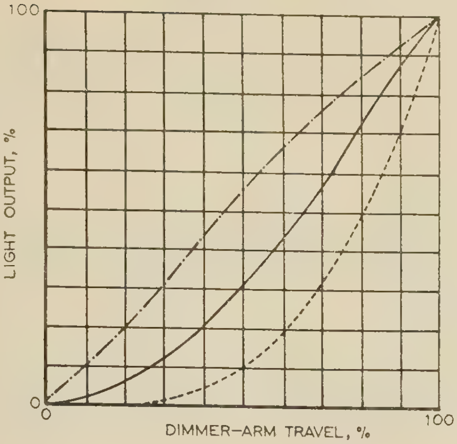

Fig. 2.—Variation of light output with dimmer-arm travel.
---- 0·5 kW lamp.
—— 1 kW lamp.
—·— 2 kW lamp.

A track is put on two sides of the winding, so that one transformer is shared by two 2·5 kW dimmers. Alternatively, the arms can be mechanically coupled and the output paralleled through a choke on the same frame to make a 5 kW dimmer. To secure a suitable winding in the limited space available, the bottom 12% of the turns are put on the limb of the core which cannot be tracked by the brush. When the dimmer arm reaches the lowest point of its travel, a limit switch trips the circuit contactor. This tracking of only the light active part of the winding has a beneficial effect on the light output curve [see Fig. 1(*b*)]. The unit is exactly interchangeable in drive with a pair of resistance dimmers, and thus mixed banks of resistors and transformers are possible and initial outlay is reduced.

(2.3) Direct Operation

Compact radial dimmers, whether resistor or transformer, have encouraged back-of-panel mounting with direct operation by links to handles in front. This is common practice in Britain and the United States, but the remote tracker-wire method—which was essential with the original liquid dimmers—has persisted on the Continent, first using metallic resistors and then transformers.

(2.4) Multi-Way Transformer

The auto-transformer dimmers used on the Continent take the form of several dimmers to one transformer and, although there are several variants, the basic Bordoni principle, as it is called, is common to all. Electrically these units—which range from 4 to 54 dimmers on one transformer winding—are excellent; commutation is direct to a flat surface (machined on the actual winding) using a 5-leaf brush, whose contacts are bridged by resistors carried on the brush frame and which slides vertically, with tracker-wire lift and gravity return. Common loadings are 2 kW per slider, but some larger sizes are used. Because many dimmers are formed on one transformer the cost per way is attractive.

(2.5) Remote Operation

Operation by tracker wire led to compact remote regulators, because the lever centres were not governed by dimmer size; however, this type of dimmer is not amenable to remote electric operation, and where lead-screws and reversing motors have been used, crude and unreliable facilities resulted.

The first large remote control installed in England (Covent Garden Opera House, 1934) uses 130 resistors connected to a common driving shaft by pairs of electro-magnetic clutches. A 2-way-and-off switch drives each dimmer up or down, the position being given by a pilot potentiometer linked to it and indicating on a dial above each switch.

The clutch is simple, consisting of a 15-volt electromagnet on a pivoted arm on either side of an iron wheel fixed to the shaft. The shaft is unidirectional, reversal being achieved by linking alternate magnets over and under the dimmer-arm pivot. In its present form (Fig. 3) the arms are die-cast and the dimmers are

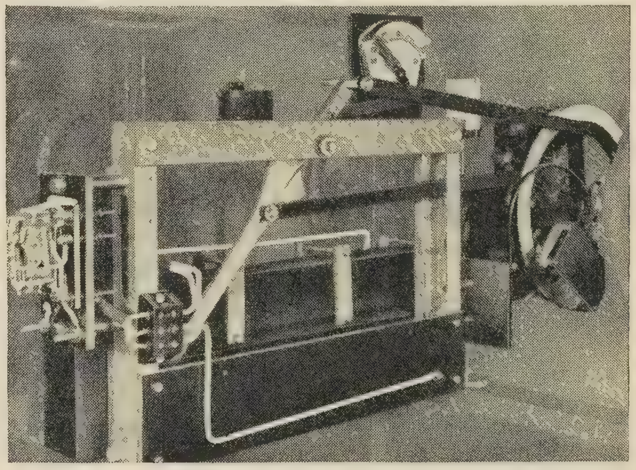

Fig. 3.—Auto-transformer with clutch servo mechanism.

mounted at 5 in centres. In the Figure the clutch is shown driving a transformer and forming part of a servo mechanism made possible by the availability, five years ago, of a compact and economic centre-stable polarized relay. The centre wire of the slave potentiometer, which is linked to the dimmer, is connected through the coil of the relay to a corresponding control potentiometer. When the latter is moved, the relay switches in the appropriate clutch and the dimmer travels at the speed of the driving shaft until the relay circuit is balanced once more.

(3) ALL-ELECTRIC DIMMERS

Several dimmers requiring no mechanical moving parts are available, and may be classed in historical order as saturable reactor, indirect electronic, direct electronic and magnetic amplifier.

(3.1) Saturable Reactor

Although in principle available for many years, the saturable reactor has come into extensive stage use only in the past seven years. Relatively heavy control currents and a variable-load performance no better than that of a resistance dimmer, plus the drawback of full-on voltage drop, restrict its use to small stages. However, used with simple circuits it does make remote control economically possible in such cases. In their earlier days saturable reactors were expensive and difficult to obtain and consequently were considered only for very large theatres. The control facilities which a large theatre with many dimmers requires are such that the simple reactor is unsuitable, so that thyratron-controlled reactors began to be used in the early 1930's in the United States.

(3.2) Indirect Electronic

The use of grid-controlled rectifiers means small currents at the control desk, which facilitates design there, but they also make it possible for the load to influence, through feedback, the current fed to the saturating coil, thereby improving the variable-

load performance of the reactor. There is only one important stage installation on these lines in this country, namely the Odeon Cinema, Leicester Square, London (1938).

(3.3) Direct Electronic

In the last 10 years it has become possible to employ the larger thyratrons now available directly, the first two systems being the Izenour (two valves per dimmer) in the United States and the Wood (three valves) in Britain; both are now in extensive use. Two thyratrons are used back-to-back in the Izenour system and the stage is fed by an a.c. supply; a booster transformer must be used to compensate for the voltage drop across the valves and the stage load must be balanced. The Wood system employs one thyratron per phase and feeds the stage with unidirectional current. No booster is required, but a transformer or a static balancer is essential, because the whole of the lighting load passes through a common return which can hardly be described as the neutral (Fig. 4). A combination of three MT57

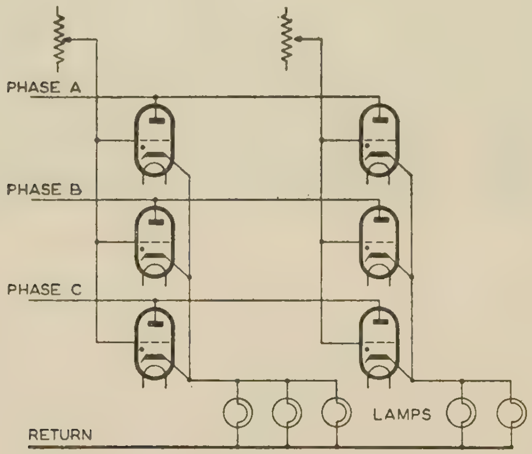

Fig. 4.—Connection of two 3-valve dimmers.

valves will control a 2 kW load at 220 volts. In America, with 120-volt supplies, the C16J valve is used to give 4 kW per dimmer (or 5 kW with reduced life) on the Izenour system and 6 kW on the Wood, the real advantage of the latter being the absence of phasing problems when patching is used.

(3.4) Magnetic Amplifier

This is the most recent system to find favour. Several television studios use it in the United States and there are some Continental stage installations. The basis is the saturable reactor, but the load is fed via two metal rectifiers connected back-to-back, and it is thus self-saturating and can be controlled with less than 2% of the normal m.m.f. A pre-amplifier and feedback are used, and the result is a good variable-load range, rapid response and a primary control current of about 20 mA at 20 volts. A booster is necessary to compensate for the reactor voltage drop of 10%.

The magnetic amplifier has a power factor of 0·9 when the lamps are full on, but since dimming is by reactive voltage drop, it becomes 0·75 at half light and 0·4 at one-quarter.

High initial cost threatens the use of magnetic amplifiers as dimmers in Britain. In consequence, a compromise has been adopted wherein the majority of circuits in an installation will have saturable reactors with a second stage added to reduce the control current to levels acceptable for presetting. Only essential variable-load circuits will have magnetic amplifiers—at present, at any rate.

(3.5) Relative Efficiency

It is of interest to compare the electronic dimmer with the resistance type. Both on the stage and in black-and-white television the 2 kW size is commonest to-day, although the stage will generally load it to 1 kW and television to 2 kW. The fomer will use a large dimming range, but the latter will never 'hold a check' (as it is called) below half light, i.e. a drop to 72% of full voltage.

A 2/1 kW resistance dimmer shows no loss when fully on or off, but it dissipates 17·8% of the nominal lamp power at 50% full light output, 27% at 25% output and 36% at the worst position, namely 3·3% output.

Three MT57 valves will require 67·5-watt heaters when the lamp is off and this plus a 10-volt arc drop across the valves when the lamp is fully on. The total circuit power, plotted from an actual test, is as shown in Fig. 5, the broken line showing that this

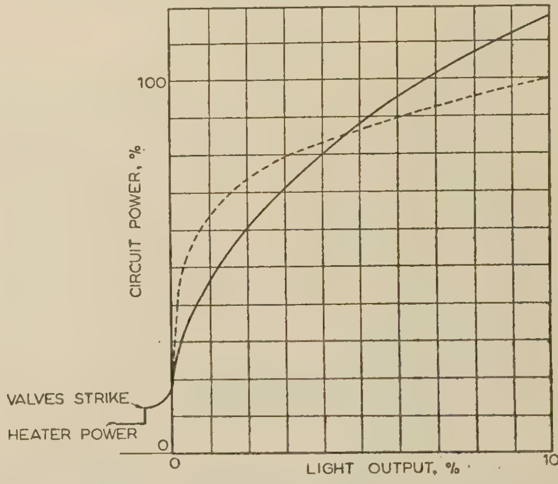

Fig. 5.—Variation of light output with circuit power for 1 kW lamp on 2 kW dimmer.

——— 3-valve dimmer.
– – – – Resistance dimmer.

electronic type is advantageous only between half light and just before no light. The amount of dimming varies considerably with the type of stage production, but it is safe to assume that the two commonest dimmer positions are fully on and off. This applies with even more force to television. The wasteful performance of electronic dimmers is confirmed in working by the fact that the rooms containing them are hotter and need more ventilation than those containing resistance dimmers.

Too much can be made of efficiency, and the choice of dimming method depends on factors which are discussed later. The subject is raised as a corrective to the commonly held belief, which condemns the resistance dimmers as wasteful compared with electronic ones.*

(3.6) Dimmer Levers

When remotely controlled, both all-electric and servo-driven dimmers can have a control knob or lever which appears the same to the operator. A vertical lever is essential to allow close banking of the many individual dimmers, and one which mounts at 1 in horizontal and 6 in vertical centres is convenient. This allows a clear scale of 0–10 (0–100% light), with half divisions marked, and permits a knob of a shape and size suitable for finger, rather than hand, working. Pairs of levers, particularly pairs of preset levers, can share a single scale, and their spacings are thereby in

* e.g. Discussion on 'The Royal Festival Hall: Electrical Installation', *Proceedings I.E.E.*, 1955, 102 A, p. 417, penultimate paragraph.

effect reduced to $\frac{3}{4}$ in. Multi-preset systems require miniature levers so that the large number of repeat levers can be housed in a small space. Several forms exist but tend to be trying to eyes and/or fingers.

(4) LOAD SWITCHING

For remote-control systems, resistance and transformer dimmers require a switch in series with each to cut the light instantaneously, for it is impossible to dim fast enough to imitate switching. Electronic dimmers can be switched by grid control to achieve such effects, although, in fact, group contactors with time delays must be fitted to prevent the valves being loaded before the full preheating has taken place. Saturable reactors and magnetic amplifiers must have contactors to unload them when lamps are dimmed out and to isolate socket-outlets. Tablet switches in which the lever acts as the label are preferred, because they are economical in space and give good indication in poor light.

(5) STAGE LIGHTING

Stage lighting comprises a large number of individual circuits for spotlights and a small number of bunched circuits for floodlights. For the majority of stages, the spotlight circuits are likely to carry 0·5–1 kW and the floodlight circuits 1–2 kW, and the variable-load range could therefore be covered by either resistance dimmers or simple saturable reactors. In large theatres there will also be a few very heavy-current circuits for lighting the backcloth or the Cyclorama. Only a few specialized circuits for lighting 'properties', i.e. the chandeliers, fittings and fires, etc., needed to dress the scene, strictly require a large variable-load range.

All circuits should terminate in groups of socket-outlets, with individual or parallel supply as required. These feed the horizontal rows of lanterns over the stage (known as 'battens') and the vertical rows at the sides (known as 'boomerangs' or 'ladders'), as typified in Fig. 6.

All this equipment is movable and may change considerably with each production, although in repertory theatres, where there are frequent (perhaps daily) changes of production, a large semi-permanent installation is the rule, to avoid too much movement of lanterns. Examples of such theatres are the Covent Garden Opera House, the Stratford-on-Avon Shakespeare Memorial Theatre and the Royal Court Theatre, Sloane Square. In all cases a large amount of spotlighting will be permanently mounted in the auditorium, often fitted with direct-solenoid, or solenoid-selected motor-driven, remote control to change the colour filters. This often means that a large amount of auxiliary switchgear must be accommodated at the main control, and only the light console and its derivatives have offered a serious solution to the problems involved.

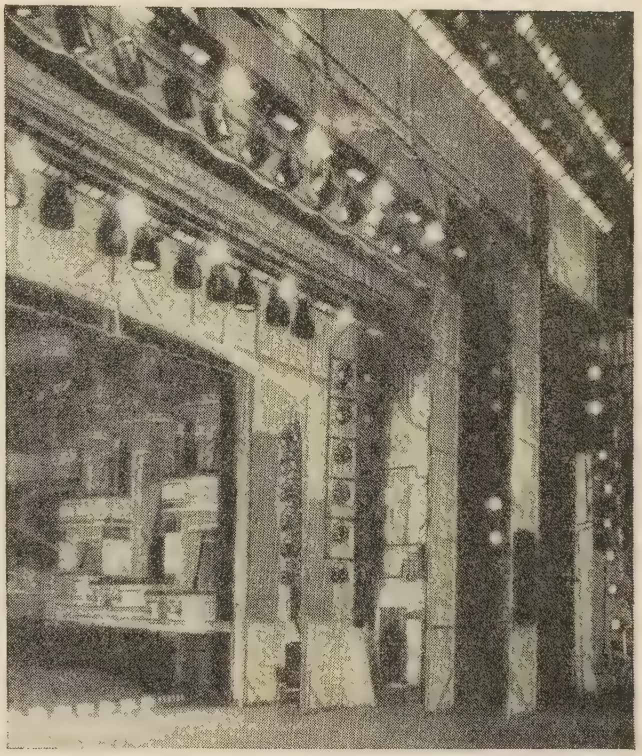

Fig. 6.—Lighting ladders and battens at the Drury Lane Theatre.

Except on very small stages, where rigid economy is essential, each circuit has its own dimmer, switches and other facilities at the central control board, the whole being known as a control 'way' or a 'channel'. The large opera house may have a small percentage of circuits so rarely required as to be subject to patching to fewer channels. Small halls and little theatres may also have to patch, to share a few dimmers among the greater number of circuits. Control boards with this feature are described as 'flexible', and patching is extensively practised in the United States—where the term originated.

Some idea of the increase in the number of individual dimmers

Table 1

INSTALLATIONS AT SOME REPRESENTATIVE LONDON THEATRES

Theatre	Dimmer		Control	Filter change circuits	Date
	Number	Type			
Coliseum	216	Electro-mechanical	Light console	32	1952
Stoll	176	Electro-mechanical	Light console	25	1950
Palladium	152	Electro-mechanical	Light console	94	1949
Adelphi	152	Electro-mechanical	Light console	70	1954
Old Vic	120	Electronic	1-preset	24	1950
New	134	Electro-mechanical mixed	2-preset	60	1955
Sadlers Wells	120	Electro-mechanical mixed	Console-preset	100	1957
Piccadilly	120	Electro-mechanical resistance	Console-preset	80	1957
Criterion	54	Saturable reactor	2-master	None	1956

The stage main capacity is 600 kVA at the Coliseum, 230 kVA at Sadlers Wells and 84 kVA at the Criterion.

is given by comparing the 56 direct-operated resistors with which the Stratford-on-Avon Memorial Theatre opened in 1932 with the 144 electronic units which replaced them in 1951. When discussing remote stage-lighting control, 36–72 dimmers is considered a small installation, 100–152 is a medium one, and 176–300 is a large one. Specific examples of London theatres are given in Table 1.

(6) LIGHTING PROCEDURE AND USE OF DIMMERS

During the lighting rehearsal, suitable circuits are switched on and the dimmers are set by visual trial and error to suit the producer of the show or—more rarely—his lighting director. The dimmers are set 'checked' to various levels to balance, or to put out of balance, the light from one source with that from another, or to mix colours from several sources, the aim being to 'paint' a particular 3-dimensional picture with light. The operator will then plot the state of his control levers so that he can subsequently reproduce that effect on cue. However, absolute finality cannot be expected when serving artists, so that he has to cope with second thoughts which continue to appear right up to, and even after, the first night. The next lighting picture is then set and plotted, and so on until all lighting has been determined. Often the change from one picture to another takes place in view of the audience, since it has a deliberate dramatic effect to make.

The dimmers thus have to be moved to change from one set of levels to another, and the rate of this change is most important. The most obvious example is a gradual dawn or sunset, where the change may have to be so discreet as to be virtually imperceptible. On the other hand, changes may be sudden, to imitate the switching of lights in a naturalistic room, or to form a rapid sequence as part of a dance routine in ballet or revue. In this last case, the precision of dimmer positioning will take second place to rapidity of operation, but some intermediate levels are always likely. Most changes involve a greater or lesser number of dimmers at a time, and thus operation concerns varying groups of these.

The composition of the groups can seldom, if ever, remain constant during a performance; nor is it likely that particular dimmers can be allowed to take up the same levels each time they are used. Thus, the operation of a stage control involves continual grouping and regrouping of channels whose levels vary from time to time and, in fact, may sometimes—officially, at any rate—never rest.

The audience is often unaware of this activity: first, because, to borrow a musical term, it is the accompaniment and must not draw attention to itself; and secondly, because some changes really are simple, but the method of demanding them makes them difficult to work. The demand may come from the drama, which bunches several lighting cues together, or from sheer ignorance on the part of a producer, which causes him, in effect, to fight the instrument his operator is using.

(7) DIMMER GROUPING

A simple way of forming groups is to use a 3-position switch above each dimmer lever and two master dimmers (Fig. 7). In this way, two groups of lighting, whose individual dimmers are set to various levels, can be moved by two controls. The centre point of each switch connects to live (independent of masters) to hold a third group (the sky effect, for example) stationary.

A second switch to each channel feeds its contactor; when it is in the top position, connection is to one master switch (blackout) and when it is in the bottom position, connection is to another; when it is in the centre, the circuit is unenergized.

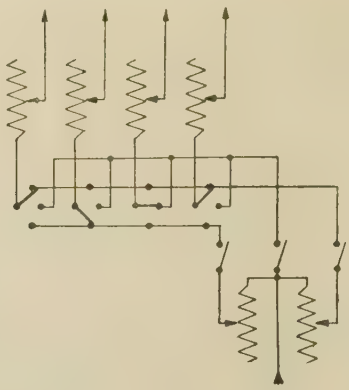

Fig. 7.—Grouping circuits for two master dimmers and independent.

One can now set up five groups to be used, separately or in combination, all of which can be subject to further modification by hand as time permits while the show proceeds.

The master blackouts need not be used specifically for switching cues, but can cut or add circuits to the master dimmers under cover of darkness. A typical sequence, often found in intimate revue, is to finish a number on a blackout and immediately follow with the new item presented in two rapid dim-ups, the first as a picture and the second as a full-up for comedy. To do this, the dead blackout is opened and the master dimmers are run down. The master blackouts are then closed or opened to add or subtract and the master dimmers run up on cue.

The circuits just described can easily be applied to saturable-reactor dimmers, and provided that there are not more than 54 dimmers, the control might be considered to be reasonable. What cannot be done is to preset the next change in respect of channels already in use. If Nos. 1–12 on the spot batten have to change simultaneously from one set of differing levels representing evening to another representing evening plus artificial light, presetting will be necessary.

(8) PRESETTING

The term 'preset' must be applied only to those controls which permit new lighting changes to be set up in respect of circuits already in use. To do this with an all-electric system necessitates a second set of levers and a cross-fader; this is impractical with a single-stage saturable reactor, because the relatively heavy control currents make the repeat dimmer levers and cross-faders too large and too expensive. Once the control is brought down to 5 watts or less, the most satisfactory circuit is that shown in Fig. 8, where each preset potentiometer feeds the dimmer via a diode, and feedback into other preset networks is consequently blocked. Particularly valuable is the ability, where there are

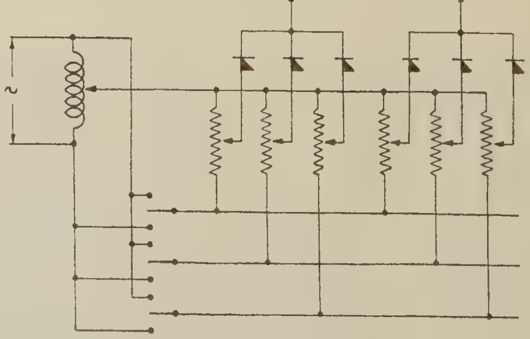

Fig. 8.—Basic circuit of preset controls for two channels.

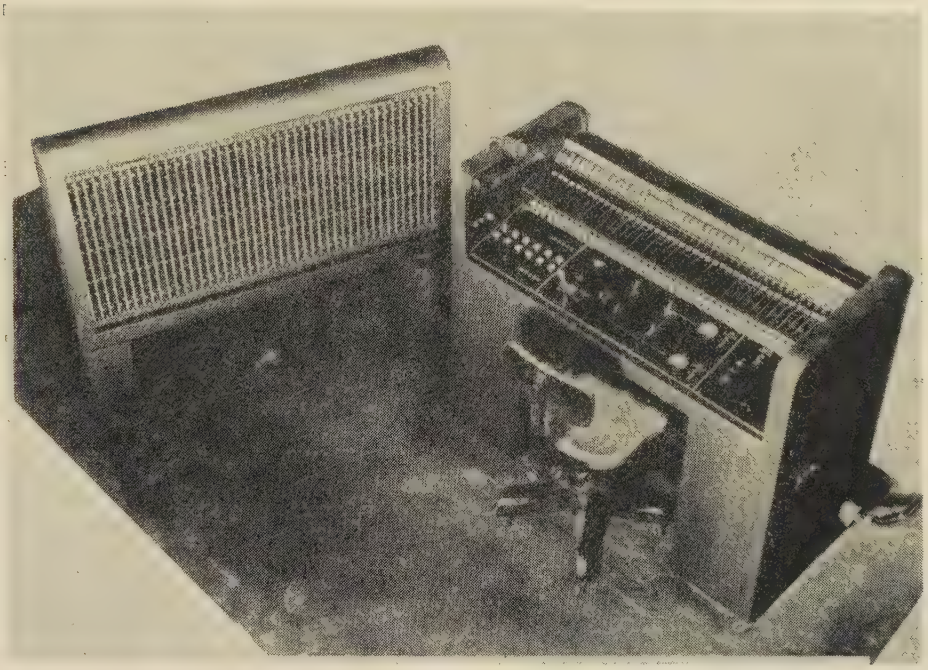

Fig. 9.—A 44-channel desk with 10-preset wing.

several presets, to add ('pile') the contents of more than one as signals to the dimmers. It is important that cross-fading should not disturb circuits which are set at the same levels on both sides of the fader. Greater flexibility of control results if twin master dimmers are used instead of the usual cross-fader.

The electronic preset controls originating in this country have employed duplicate control desks, so that one can be used to hold the lighting while the other is preset. Each dimmer on each desk has a 3-way switch for grouping on row-master dimmer or independently; rows in their turn can be coupled to a grand-master dimmer or to an independent master. Each row can also be held independent of the cross-fader, to avoid having to set a whole row of exactly duplicate settings.

Duplication of settings on each desk for circuits that do not change is exacting and time-wasting; consequently, in television, where precise matching is important, the presets are better as twin levers side by side. This may be a drawback for the theatre, in that some simple changes become complex; e.g. if the left desk has to be set to full-up, levers can be rapidly pushed up with the flat of the hand, whereas on the twin systems the odd numbers must be picked out.

There are now three quite different approaches to the problem of how to get more rapid precise work out of a preset dimmer board, namely the multiple-preset (United States), the electro-mechanical desk (Germany) and the electro-mechanical dimmer bank (England).

(9) MULTIPLE PRESETS

This system has been in use for many years, an early (1933) example being Radio City Music Hall with six repeat levers, i.e. five presets and a rehearsal lever to each of the 314 dimmers. If for no other reason than space, group masters and such switching cannot be repeated for each set of levers, so that the practice is to have one set of larger levers with all such facilities (the rehearsal system) and repeat dimmer levers only—often in miniature—as presets. At the Yale University Theatre, in 1947 (44 electronic dimmers), and subsequently, the ten presets were logically separated to form a wing panel on one or both sides of the desk at which the principal operator sits to work the rehearsal system (Fig. 9). Each channel can be transferred from preset to rehearsal control by means of a switch under the latter lever. A cross-fader allows the change from one preset to another or to blackout, each side having selector switches for the purpose.

The aim is to work out the lighting on the main desk and to store the larger changes in the wing panels. This is rather tedious, since an installation of 100 dimmers (e.g. Theatre 72 of the Columbia Broadcasting System, New York) means 1 000 miniature levers to set. For the theatre, operational dexterity on the rehearsal system can supplement and render the 10 presets adequate for most productions. In the Brooklyn colour studios of the National Broadcasting Corporation in New York

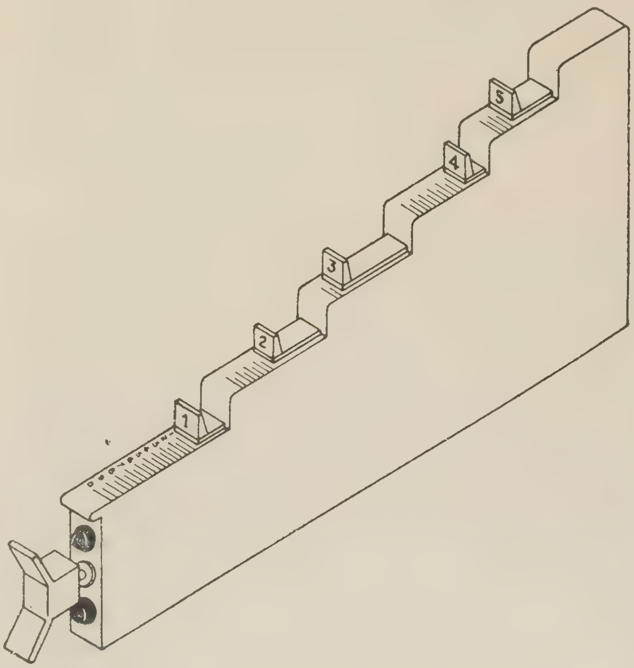

Fig. 10.—Tiered 5-preset dimmer lever unit.

80 magnetic amplifiers are controlled from tiers of levers derived by Lustig from the Hammond organ tone slider (Fig. 10). By building the 10 presets as a slope, the problems of distance and height relative to the operator are somewhat ameliorated. There is no rehearsal system, but the bottom row of dimmer levers can be switched from 'preset' to any group master (there are eight to choose from). The presets themselves have their own masters, in addition to the cross-fader. In fact, the arrangement involves a network of routes and counter-routes which demands pre-meditation, the idea being that, once set, the various masters will be invoked and the amount of individual dimmer working be negligible. Nevertheless, from television has come the demand for 20 presets which nobody has yet found a practical way of satisfying.

(10) MECHANICAL-DIMMER REGULATORS

(10.1) All-Mechanical

In Germany, the State Theatres, of which there are sometimes three or four to a city, stage productions on a scale unknown in Britain, except perhaps at Covent Garden. Opera houses require between 200 and 300 channels, a few of which may be augmented by patching. Prior to the war, these were catered for by Bordoni dimmers, tracker-wire operated from compact mechanical regulators with levers at $1\frac{3}{4}$ in horizontal centres on shafts at about 14 in vertical spacing. Each lever could be locked by handle movement to travel either up or down when its shaft was operated by master gearing at the end. A degree of preset was obtained by pulling a shutter down over the top end of the lever track or up from the bottom end, thus limiting the travel. This system is common in theatres all over Europe, but, except for the Glyndebourne Opera (1934), it has never become accepted in Britain.

Post-war practice has continued on the same lines except that, as at Bayreuth and Vienna, the shaft master drive is often by motors with Ward Leonard speed control. However, a magnetic-amplifier system from Sweden and the electronic system from England began to set a new fashion in Europe. First Italy, then Germany, developed their own dimmers using these techniques, but, strangely enough, did not utilize the circuit potentialities at the control end. Thus, mechanical-type regulators had the sole advantage of being rather more compact (1 in centres) than their predecessors, and of electrical, instead of mechanical, connection to the dimmers. Recent examples are the Augsberg and Dusseldorf opera houses (1956: magnetic amplifiers).

(10.2) Electro-Mechanical

For the new Hamburg Opera House (1956: electronic) there are 260 channels duplicated on two desks, giving together one electrical preset ahead. Each channel can be individually switched to either of two group masters for its area and to either of two cross-faders or independent of them. Nevertheless, it was realized this would be insufficient, for resetting 260 channel dimmers would take an impossible time. Resort has therefore been made to a mechanical cam system within each channel lever on both desks, which can store four intermediate lever positions plus full-on. This enables whole groups of levers to be moved to their new levels. The method of setting is to put the dimmer levers to the required levels and then drive a group of preset cams by means of a master wheel until they take up corresponding positions. When using the preset the reverse procedure takes place and the cam trips the dimmer lever at the correct position. The setting of each cam shows as a small scale under the main dimmer scale, which is engraved on transparent plastic.

The mechanical presets are used to move the levers while the other desk is actually holding the lighting, but they roughly double the size of each desk. The drawback (apart from the mechanical complication) is that, although all controls indicate their state, it is difficult to make a rapid appraisal of the present lighting and the next change to come. Although certain productions are easy, it must take several months of experience before operators can feel at home in an elaborate production.

A more easily comprehended system has been developed from the Augsberg type of desk referred to above and is under construction for the Mannheim Opera House. The clutches for dimmer-lever grouping, which are in fact electromagnetic in action, have been made part of a polarized-relay servo mechanism. The servo system of the 200 levers on the main desk can be connected to any of four sets of preset levers on an ancillary desk. Thus the whole set of main dimmer levers can be driven at varying speeds to take up positions corresponding to any set of preset levers. The main desk levers which control the remote magnetic amplifiers can, however, be modified at any time by hand. It is suggested that, where necessary, the ancillary desks will be repeated and eight or twelve presets provided thereby.

(11) ELECTRO-MECHANICAL DIMMER BANK

The first important installation was in the Covent Garden Opera House, but the author has always disliked a switchboard approach to lighting control. An organ console has for some years been a complex switchboard, but to the organist it is an instrument. The modification (1935) of the organ-console form to suit lighting was a natural step to take. This system, known as the light console, was not really accepted until 10 years ago, and it is now installed in the London Palladium, the Drury Lane Theatre and a dozen or so of the larger theatres devoted mainly to spectacle.

(11.1) The Light Console

In the organ, circuits are selected by putting stopkeys down for the required stops (tone colours), singly or in combination, which are then played on a keyboard. To convert to lighting, the stopkeys can be used for each circuit, but the keyboard must apply sustained action. Whereas when a stop is put off, the organ pipes cease to sound, on the light console the lighting remains in its precise state at that moment and will continue thus until further instructed. Space is greatly reduced, because each channel is represented by a single switch only. Stopkeys are not only easier to handle than any switch, but are ready made with the automatic group facilities known as 'instantly adjustable combination pistons' or, more recently, as 'memory preset'. A representative arrangement is shown in Fig. 11, and in a large installation such a group of about 40 channels will be repeated several times and be associated with particular groups of lighting. At the Drury Lane Theatre there are six groups totalling 216 channels spread over three keyboards. The latter have two touches ($2\frac{1}{2}$ and 12 oz): the first touch will raise the dimmers and the second will lower them.

Fig. 12 further illustrates the principle. As each stopkey is put down, the corresponding relay bar is raised to the ready. When a manual key is pressed, a tracer is drawn down, causing individual contacts to make on any raised stop bars. The contacts on the tracers go respectively to the 'up' or 'down' dimmer clutches, the blackout or full-on contactors, the indicator, reverse and five colour-filter circuits. The amount of movement applied by holding a key is shown by driving a dummy dimmer known as a 'setter'. This indicates on a dial and resets to zero each time its group key is released. Groups are identified by colour, but this may have no actual relation to the lighting colour.

The speed of dimmer travel is regulated by balanced 'swell'

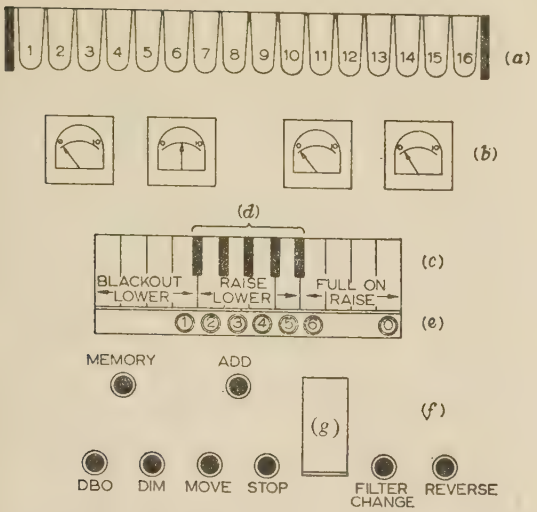

Fig. 11.—Basic controls on light console.

(*a*) Stopkeys.
(*b*) Indicators.
(*c*) Master keys.
(*d*) Filter keys.
(*e*) Combination pistons.
(*f*) Foot pedals.
(*g*) Speed regulator.

(*a*), (*b*) and (*c*) repeat in fours as white, red, blue and green.

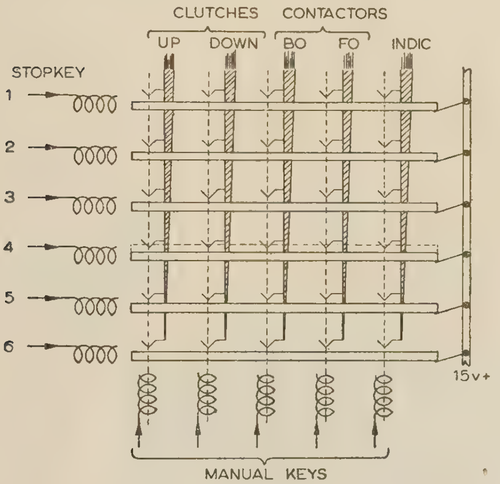

Fig. 12.—Schematic of cross-relay for light console.

pedals. To read the actual position of an individual dimmer, its stopkey is pressed to a second deeper touch and its setter dial changes over.

It can be seen that the light console uses its masters for all movement and that channels whose stopkeys are put off remain in the state to which they were last set. This is an important feature of an electro-mechanical dimmer system. Controls need not be used to hold station; inertia will do that. Thus, once a lighting change has taken place, the controls can be set for the next change and then only in respect of those channels which have to change.

The drawback of the light console is the difficulty of obtaining a variety of intermediate dimmer positions. If the dimmers start at zero it is not difficult to trip the stopkeys by hand or by combination pistons, automatic or manual, as the dial passes the various levels. But if the dimmers are initially at various levels and have to move to others, the working-out and setting-up required can be tedious. Altogether, a lot is expected of the operator, and a good view of the stage is an essential aid to him.

Nevertheless, operators seem to learn the job in two weeks, and for spectacular productions, with many—rather than meticulous —changes, the device appears to be satisfactory. Certainly it has replaced nine men on the old switchboards by one man and a deputy at the London Coliseum.

(11.2) Dimmer Preset Switchboards

A twin-desk preset of 134 channels with a polarized-relay servo mechanism was installed in the New Theatre in 1955. Because both networks can be uncoupled from the dimmers, it gives two presets ahead instead of the one offered by its electronic predecessor. As with the latter, but not the light console, it is still impossible to dispense with the repeating of lever positions for dimmers which have no change. This is because there is no convenient and rapid way on a switchboard of immobilizing the many varying groups of channels.

(11.3) Console Preset

To make the most of an electro-mechanical dimmer bank, organ stopkeys must be combined with dimmer levers (Fig. 13).

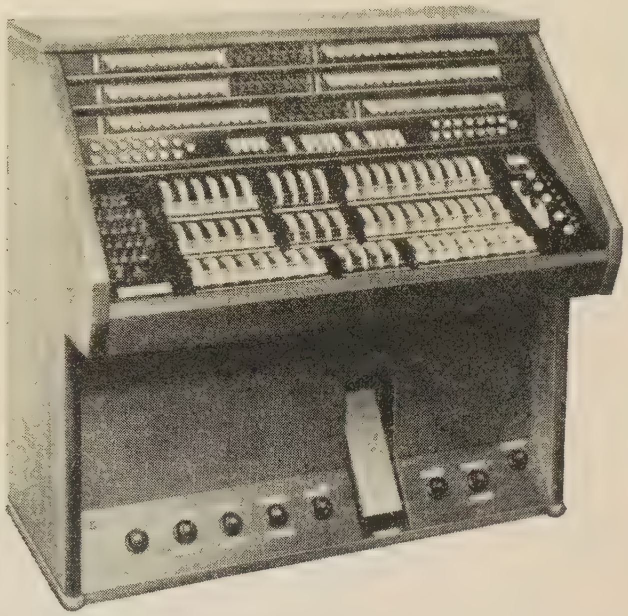

Fig. 13.—The 120-channel console-preset desk at the Palace Theatre, London.

The potentiometers in the centre of the desk can be coupled to the coils of their polarized relays, but the centre contacts of the latter receive mains supply for the servo clutches from the channel stopkeys. Thus, although a preset coupler is closed and the shaft motor is turning, only dimmers whose stopkeys are 'on' will move.

A similar principle is adopted in respect of the circuit contactor, which normally holds 'in' but can be ordered 'out' by the same stopkey in conjunction with the blackout master push. It follows that, because the operator has to set dimmer levers only for those channels which have to change, he no longer has the exacting task of matching for no change. Of course, there is an extra operation, but the stopkeys are handy to work and have memory preset action. For this latter facility each stopkey has a pair of magnets to move it, and the 'on' and 'off' coil contact is captured in a cross-relay. This relay has a notched twin bar to each stopkey and vertical tracers back and front to energize and to set the combination respectively. Fourteen or 20 com-

bination pistons and one master-setter toe piston are provided, the whole action fitting inside the console desk.

It is natural that the type of wiring (15 volts d.c.) and switching used in an organ console should become common for the dimmer bank. Organ practice uses silver-wire contacts, and relays making common to 16 or 24 contacts or couplers making 61 individual contacts separately are compact.

If channels are selected on the stopkeys and the coupler to the polarized relays is closed while the desk potentiometer network has only its positive or negative mains terminal connected, the corresponding dimmers will drive up or down without the need to move their dimmer levers. In combination with a setter dial to register amount of movement, the control can be used as a light console for fast coarse movement. Because the dimmer levers may not at times indicate the actual dimmer position, the second touch on the stopkeys connects the dimmer servo potentiometer to show this on the setter dial.

(12) TELEVISION LIGHTING

Television lighting hangs mainly overhead and consists of a mixture of softlights ('scoops' or 'broads') and Fresnel-lens spotlights; which of the two preponderates depends on the type of camera used. The most obvious difference from the stage is that the theatre discipline of successive scenes on the same area facing the same way does not exist. There may be either a number of scenes set side by side round the studio, to be visited by the cameras in and out of turn, or there may be one large scene, parts of which the cameras may view from almost any angle. Moreover, no repeat productions occur, so that the lighting layout for one day will be completely different from those of the preceding and following days. Lantern rigging and wiring is the major preoccupation, and it is impossible to plan the lighting control before the method has been determined. If socket-outlets in the studio are not readily accessible at all times, there will have to be many more than will be used for a production. Then all will have to terminate as separate circuits in a patching field to connect to a lesser number of channels.

Some representative installations are shown in Table 2.

(13) PATCHING

The common method of patching is to use, for each circuit, a single-pole jack-plug with its cord retracted by a weight, as in a telephone switchboard. In the B.B.C. Riverside II Studio there are 300 of these. Control channels are usually represented by two sockets in parallel, and not all will necessarily have dimmers. To enable any cord to reach any channel on a large jack-field built-in jumpers must be provided, together with ammeter test sockets to check doubtful loads. Cords are not ideal, owing to the setting-up time, the confusion caused by large numbers of crossing leads and the size of the jack-field, which makes it difficult to place. The number of jacks becomes excessive in large studios; for example, there are 1 000 in one N.B.C. Brooklyn studio.

If limitation of choice is accepted, it will allow 15-way selector switches to be used for each circuit, as in the three Associated Rediffusion studios at Wembley. The fifteenth position gives an energized position, subject only to the circuit contactor, the other positions connecting to 14 transformer dimmers. Each studio has two groups of approximately 50 circuits, each group having 14 dimmers. These controls are therefore more concerned with switching than dimming. Experience at Wembley suggested that the installation of 320 similar selectors specified for the B.B.C. Riverside I studio would be too clumsy, although, in fact, there were some as large in the United States. A remote-control patching system using 8-way miniature selector switches in conjunction with seven 20 amp contactors was devised as a result. The important step here is the association of selection with each channel and not with each circuit, thereby reducing the number of selector switches and contactors by nearly one-half. It also avoids overloading problems, since only one circuit can be patched to a channel at any time; on the other

Table 2

INSTALLATIONS AT SOME REPRESENTATIVE BRITISH TELEVISION STUDIOS

Studio	Number of circuits	Dimmers		Patching
		Number	Type	
B.B.C. Television Theatre ..	188	188	Electro-mechanical mixed	None
B.B.C. Riverside I	348	166	Electro-mechanical mixed	Remote selector
B.B.C. Riverside II	308	96	Electronic	Cord and jack
A.R. Wembley 1, 2 and 4 ..	100 each	24 each	Electro-mechanical transformer	Selector switches
A.R. Television House 9	45	45	Electro-mechanical resistive	None
Granada Television 2 and 6 ..	102 each	54	Electro-mechanical mixed	Studio access
A.B.C. Television Didsbury 2 ..	18	18	Saturable reactor	None
T.W.W. Cardiff	124	34	Electro-mechancal resistive	Studio access

Riverside I has the largest floor area (6 000 ft²), but there are no really large studios in Britain, although some with more than 10 000 ft² of floor area are in the planning stage. There are 18 studios in all with centralized remote lighting control, giving an aggregate of 1 566 channels; all have been installed since June, 1955.

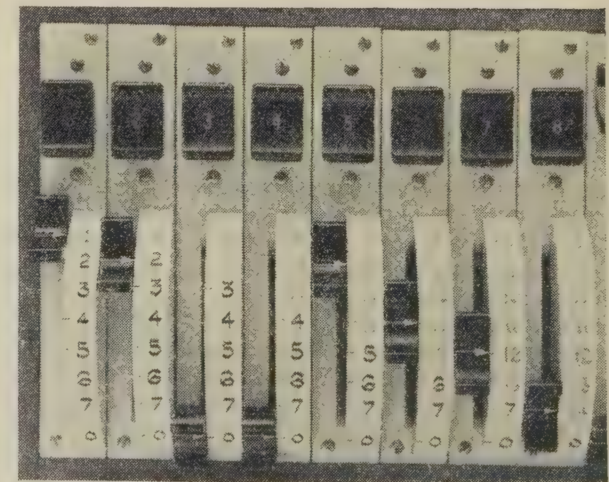

Fig. 14.—Remote patching selector: 8 channels, 14 circuits.

hand, more channels must be provided, because circuit paralleling cannot take place.

It had already been decided to use resistance dimmers for each channel, so that dimming could be used whenever necessary without repatching, and the present method is applicable only when this is done. The system assumes that, for example, eight channels can select any circuits of a group of 14. To do this, the first selector connects to circuits 1–7, the second to circuits 2–8, the third to circuits 3–9, etc., the eighth connecting to circuits 8–14. Setting-up should always take place from the ends, because these circuits have only one channel whereas the others have progressively more choice until 7 and 8, which both have seven chances. The selector switches are of the vertical, not rotary, type, mounted at 1 in centres (Fig. 14). The patching switchboard for the Riverside I studio has a working area 3 ft wide × 3 ft 10 in high, and is mounted adjacent to the main lighting control.

(14) TELEVISION CONTROL DESKS

The main task is the centralized switching of all channels, and the control of dimmers is of secondary importance. Nevertheless, many studios in the United States and some in Britain have a dimmer for every channel, so that the picture, as seen on the monitor, can be corrected for lighting balance without the delay of repatching for dimmers. This also permits all hanging spotlights to be of one size and yet to give reduced light when necessary. Dimmers are also used for stage-type lighting changes, particularly in variety or musical shows. Even with colour television, dimming by up to 20% of full voltage is practised in the United States.

Switching will principally be concerned with the various scenes around the studio. If the lighting can be eliminated in scenes outside the range of the camera, less studio ventilation and mains capacity need be allowed. At the Riverside I studio the provision for production lighting is 160 kW, whereas the total channel capacity is 344 kW. The memory preset action can be invaluable in controlling the lighting circuits for a particular scene area from a single pushbutton which will trip those in all other areas at the same time. However, it must be possible to nullify the tripping action and add two presets when a scene is nearing termination, in order to preview the next on another camera and monitor.

To some extent these simple switching operations have confused the issue in the United States, because the rows of dimmer presets needed for the stage have been used. Organ stopkey devices were not introduced there for lighting control until 1955, and then only for immediate switching.

For Granada Television, Manchester (1956), a console-preset which is a simplified version of the theatre model, but with dimmers for the odd-number channels only, has been used and has found general acceptance elsewhere.

For some studios, particularly Television House, Riverside I studio and Television Theatre, an organ luminous push, 1 in in diameter and working a reverser relay, has been adopted. When touched it lights internally and the lamp in the studio is 'on'; touched again and both go 'off'. While touched, the position of the dimmer is shown on a master dial nearby. The reverser relays have the same combination action as stopkeys, but, since these are in the remote dimmer room and only the internal lamps are affected at the desk, it is completely silent. The luminous push mounts better on switchboard-type panels, but is less suited to rapid finger work and is rather more complex to make and maintain.

The control in Television Theatre, which is at the time of writing the most complete for this purpose in this country, comprises a centre table with the master preset controls, memory presets, speed regulators and pedals (rather similar to that shown in Fig. 15). A wing section, 3 ft wide and 3 ft 6 in high, is angled at either side of the table, so that the seated operator can reach all the dimmer levers and channel pushes. Built into the table under a glass panel is a mimic diagram of the studio which reproduces (with dimming) the state of each of the 188 channels. Under each channel on-off push are the twin dimmer levers for two presets. Originally, any combination energized at the pushes was automatically 'on' in the studio, but as a result of experience at the Riverside I studio, it was altered before it

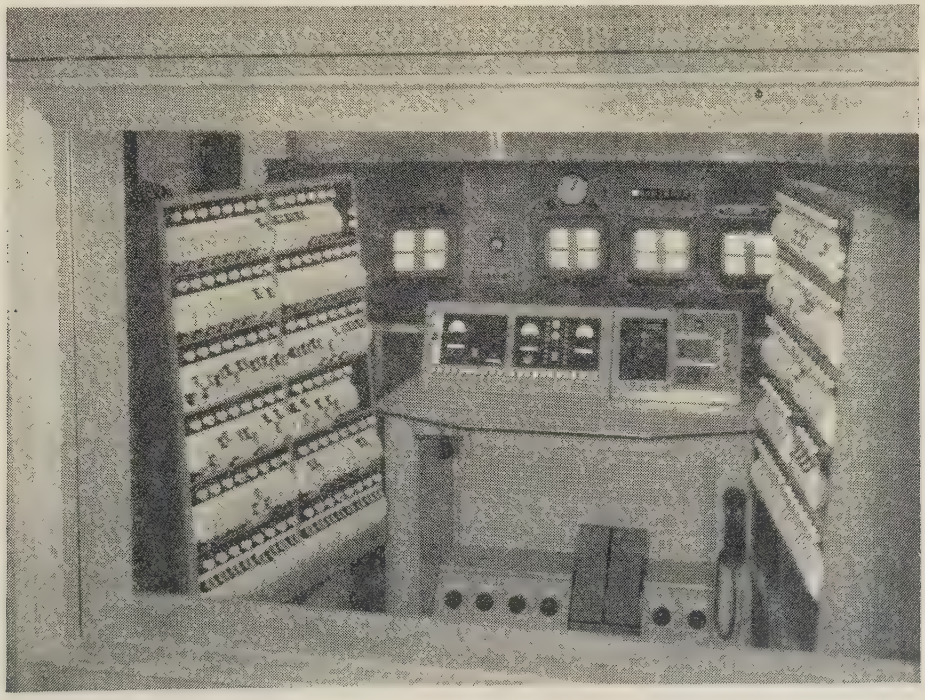

Fig. 15.—The 166-channel control at the B.B.C. Riverside I Studio.

went into use to provide selection of circuits only at the pushes. Action is now subject to master switches almost exactly similar to the theatre controls described in Section 11.3.

(15) CONCLUSIONS

The author's operational experience led him to adopt delayed-action switching for the theatre (i.e. selection then operation by master) more than 20 years ago, but immediate switching seemed essential when designing for television. This has been unnecessarily limiting, because before the channel switches are used to select a dimmer combination differing from that 'lit in studio', such lighting must deliberately be locked by means of a 'hold' master switch. However, where contactor circuits provide an inertia similar to that of the dimmers and need to be energized deliberately, the operator can approach complex changes with more abandon, confident that the normal state is 'studio at rest', not 'studio in darkness'.

An electro-mechanical dimmer bank provides an ideal basis on which to build such a control, but it is not easy to see how the inertia principle can be applied to all-electric dimmers, such as magnetic amplifiers. These dimmers are attractive, because of their immediate response, their freedom from moving parts and their potential freedom from maintenance. However, immediate response may be a limitation, and mechanical devices should not imply unreliability and an unreasonable amount of maintenance.

Control must be seen from the operator's viewpoint. That everything must be to hand goes without saying, but the controls must be as few as possible, yet be able to indicate what is happening and about to happen. Television or theatre production is not mechanical, but is a human affair with human advantages and human failings, and this works against the application of automation. Aids such as the preset memory must, at any instant, be taken from store, so to speak, examined, perhaps modified, and immediately locked up again. Last-minute changes due to inspiration or accident occur at any time, even during transmission or performance, and complex networks of controls requiring much premeditated setting-up are not flexible enough in these circumstances. Quick appraisal and the ability to conform or remedy is what the producer, the actor and the audience have a right to expect of the lighting operator and his instrument.

(16) ACKNOWLEDGMENTS

The author wishes to thank the Joint Managing Directors of the Strand Electric and Engineering Co., Ltd., for the freedom to publish material arising from his work; the John Compton Organ Company Ltd., for the inspiration derived from their organ devices; and all those on the Continent, in the United States and elsewhere who have taken so much trouble to demonstrate to him the lighting controls they have designed or which they use.

DISCUSSION BEFORE A JOINT MEETING OF THE UTILIZATION SECTION AND THE RADIO AND TELECOMMUNICATION SECTION, 12TH DECEMBER, 1957

Mr. K. R. Ackerman: I shall restrict my comments to lighting control for television. During the last three years the control facilities available have reached a high standard of development, largely because of the author's work. All the television lighting-control installations so far installed in Britain have differed in major particulars; this is to be expected at this early stage, but I should like the author's comments on standardization. I refer particularly to our problem in the B.B.C., where we have some 20 lighting supervisors who may work in any one of our seven major London studios. It is therefore extremely difficult for them to achieve the highest degree of familiarity with their desks, upon which the best results depend. This problem is not, of course, peculiar to lighting control for television. When does one call a halt to development in the interests of standardization?

I believe that the design of the lighting desk is nearing the stage where such a standardization could be effected. This might seem surprising after so short a period, but the desks now available show remarkable flexibility. I do not think that this is true of patching systems, and I should like the author's views on this subject.

The circuit selector or patch panel serves two main purposes—to reduce the number of controls with which an operator must deal and to reduce the size and cost of the installation. Some of the patching arrangements which have been proposed would fail completely on the second requirement. In other words, if a system costs more per way than the dimmer which it replaces, then obviously the patching system serves little purpose. This is a matter upon which development might well be concentrated during the next few years.

Dr. H. H. Ballin: The author gives the impression that thyraton dimming is out of date, and I feel this is not true. The 2-valve system—which, so far as I know, is of Dutch and not American origin—has been employed on a large scale with recently developed biasing systems, and in my view it is vastly superior to the 3-valve system for the following reasons:

(*a*) The output is alternating and can therefore handle both tungsten-filament and discharge-lamp loads.

(*b*) Contrary to the statement made, no booster transformer is necessary, anode-voltage drop being compensated by using lamps rated at 10 volts below line voltage.

(*c*) It can be used on single-phase supplies.

(*d*) The biasing circuit may be damped to give the equivalent of thermal inertia in incandescent-filament lamps, which has completely overcome early criticism of flicker and instability when controlling discharge-lamp loads.

A present British system for 220–250-volt supplies can control 1 kW with a pair of XR.1.1600 valves, 2 kW with a pair of XR.1.3200 valves and 4 kW with a pair of XR.1.6400 valves. These figures will give very slightly reduced life, since they represent a 5% overload on the valves. It must be stressed that these inert gas-filled valves, with short (1 min) preheating times and independence of normal ambient air temperatures, are vastly superior to their mercury-vapour-filled counterparts.

A further advantage of the 2-valve system is that it does not require group-load contactors for time-delay purposes. With the biasing systems generally used (valves normally non-conducting), delayed application of bias supply is adequate to prevent valve damage, and may be effected by means of a small process timer or the like.

Mr. J. Stap (*Netherlands*). The main difference between Continental and British practice in television lighting is our use of fluorescent lamps,* the principal reason for this being the smaller heating effect, especially where rather high lighting levels are required, as with cameras using image iconoscopes or in colour television. As an example I should like to mention a lighting fitting consisting of six parabolic trough reflectors side by side, each with a 40-watt fluorescent tube. The tubes are used with 65-watt ballasts, thus increasing the light output by approximately 35%, with a lamp service life of approximately

* MALY, R.: 'Technische Einrichtungen des Fernschstudios', *Archiv der Elektrischen Übertragung*, 1956, 10, Beiheft, p. 27.
ROOS, M. B.: 'Lighting in Television Studios', *International Lighting Review*, 1956, 4, p. 132.

2500 hours. The ballasts are outside the studio, and connection is by means of 7-core cables with 7-pole plugs and sockets.

The intensity in the centre of the beam is approximately 6000 cd, and half this at 30–50° either side. With this arrangement a base lighting of 150 ft-candles can be obtained. For colour television with image-orthicon camera-tubes, pure fluorescent light is not satisfactory for base lighting, and about two-thirds of the total must be from incandescent-filament lamps.

Mr. L. G. Applebee: Before the 1914–18 War the stage was lit by battens and footlights, which could be dimmed; directional light was provided by electric arcs, and Sir Herbert Tree's production of 'Drake' used 40, each with its own operator. The 32-way control-panel was thus quite sensational in those days.

In 1919 the projector lamp eliminated individual operators; one could harness the directional light and use dimmers. But progress towards unified control was frustrated by the theatrical proprietors, who expected much of the equipment required to be provided by the company which rented the theatre. Circuits were very temporary, and it was a long time before anybody thought of using projectors in the auditorium. However, eventually 96 dimmers were used, which was the maximum possible on a manual direct-operated switchboard. The difficulties can be imagined: 'The Death of a Salesman' at the Phoenix used 122 ways all individually controlled by dimmers, and involved 4 temporary boards in addition to the house board.

The production 'The Death of a Salesman' started the business of more ways and more ways until we reached the numbers which the author has shown in the paper.

It has taken a long time to convince the theatre architect and the proprietor that the lighting operator should be able to see everything. But we began at the London Palladium half-way through the war; at Stratford-on-Avon we took the royal box at the back of the circle, which gave a complete view of the stage. Then the London Coliseum, Her Majesty's and the Old Vic co-operated, giving control panels from which the operators can see what is happening on the stages.

Unfortunately, unlike television, there is no lighting artist employed in the theatre. We get a good electrician to work to a plot, but I believe that, with the right person on a control board in the right position, a plot is unnecessary, for the controller makes his own. We had one of the finest remote-control switchboard operators at the Palladium; she never worked to a plot, despite the high-speed revues staged. Conversely, at a theatre where the operator could not see the stage there was a day when one page of the plot disappeared, leaving the operator one page behind throughout the remainder of the show. Had he been in front he would have realized what had happened.

Mr. H. O. Sampson: The paper describes the automatic patching system in the B.B.C. Riverside I studio and the hand-operated patchcord system in the Riverside II studio. The automatic system is simple to operate and the state of patch can be conveniently checked by the operator at the lighting console; but it is complicated to work out the correct combinations, for there is a limit to the degree of interchangeability of dimmers with respect to the studio circuits, while the many contactors involved are expensive and require maintenance effort. With the hand-operated system the interchangeability of dimmers in respect of studio circuits is good and the maintenance is simple; but the mechanical process of plugging-in dozens of cords is rather confusing and makes cross-checking difficult, while the apparatus is large and cumbersome and it is impossible to determine the state of patch without entering the dimmer room and inspecting the cords. Nevertheless, as users we favour the hand-operated plug-and-cord system, because the automatic system does not give sufficient freedom of choice.

Both methods leave much to be desired, and what seems to be needed is an automatic system with an infinite choice. Has the author any views on this problem?

The B.B.C. installed the lighting console to enable theatre-type lighting changes to be performed quickly and easily and to permit lighting intensities to be balanced without the clumsy use of diffusers, thus improving the picture quality and saving time. In order to obtain optimum efficiency it was felt that the lighting supervisor was the most suitable person to operate the console, because

(*a*) The operator should have a thorough understanding of the television system in order to make the best use of the console.

(*b*) The lighting supervisor is responsible, with the producer, scene designer and the technical operations manager, for planning productions, so that he knows in advance what type of lighting effects are called for by the production and is thus the best person to achieve them.

(*c*) The console operator should possess considerable artistic appreciation and be able to understand and interpret the lighting effects which the producer requires.

In Section 14 the author states that, in American colour television, dimming by up to 20% of the full voltage is practised. Will the author describe any personal experience he has had in the United States and say whether the lamp dimming, and consequent reduction in colour temperature, was applied in acting areas where flesh tones were concerned, or was it confined solely to background variations for the purpose of scenic effects?

Mr. P. E. M. Sharp: My experience of switchboards has been mostly on the operating side in amateur dramatics: I have encountered a variety of these boards, but not of the more complex type described by the author for television. One of the great difficulties of the lighting engineer or operator is recording the positions of dimmers and cues. With a limited number of rehearsals the most serious problem in performance is repeating what was done (and probably changed innumerable times) earlier. This must apply in even greater degree to the complex problems of television. It must also apply to such features as 'Son et Lumière', where there may be some 200 changes to make in less than an hour.

One way to overcome this is to use an organ-type console, the pistons of which can be readily altered to give a number of preset combinations; but on the console shown at the meeting there were only 14 preset combinations, so that the operator must still make elaborate notes. The problem is similar to that in the use of computers, and suggests the possibility of a punched card recording the preset combination, or perhaps an even more complex information storage device such as a magnetic drum. We can then perhaps ultimately achieve the state where the whole operation of the switchboard is carried out by predetermined cues from the actors' speech.

Mr. P. P. Eckersley: Two aspects of television pictures impress me, namely that the cameraman fidgets too much and that the pictures are, in any case, rather flat. The somewhat elaborate lighting control systems described would seem to tempt the operator to fidget even more; and however much he fidgets, 'the more it changes the more it is the same thing'.

Mr. A. W. Gostt: As a novice in this specialized field of electrical engineering and lighting, I am fascinated by the complexity of the lighting supervisor's task: he could more appropriately be described as the lighting engineer-artist. He must not only know in great detail how to operate the complicated control panels, but must be familiar with what goes on on the stage or television-studio floor and be well-informed about television cameras and their associated techniques. How long does it take to train a lighting supervisor for this work?

[The author's reply to the above discussion will be found overleaf.]

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. F. P. Bentham (*in reply*): I agree with Mr. Ackerman that in control desks for electro-mechanical dimmers we should now expect the same facilities placed in familiar positions, although there is still a sharp division between those who prefer the dimmer preset levers adjacent to each other and those who prefer them mounted as separate panels. I prefer the latter for theatre work, but for television one cannot be so certain. Policy can determine which form is adopted within one organization (such as the B.B.C.). However, a change to an all-electric dimmer lacking inertia inevitably leads to quite different principles at the control desk.

Dr. Ballin.—In my experience, the electronic dimmer constitutes a very small proportion of the dimmer ways installed during the past two years, whereas 5–6 years ago it was all the fashion. One of the principal reasons for this decline is heat loss, whatever the system.

Izenour was the first to show how to assemble a large number of 2-valve dimmers as a control, and this is the relevant problem in this context, not the form of the individual dimmers themselves. My views on Dr. Ballin's reasons are:

(*a*) While it is true that an a.c. output is useful because discharge lamps can be handled, these form too small a proportion to influence the form of the main lighting control installation.

(*b*) This is an evasion; lamps available in differences of 10 volts are peculiar to this country and the sooner we stop the tradition the better. In any case, where—as frequently in television studios—some 50% of the circuits are switched directly, two lamp voltages cannot be tolerated.

(*c*) True, but it does not suit 3-phase supplies, which are normal to all but the smallest installations. If anything would attract me to thyratrons it would be the lack of balancing and 400-volt problems with 3-valve dimmers, especially where patching is used.

The C16J referred to in the paper is an inert-gas-filled, not a mercury, thyratron. The Riverside II installation uses 96 sets of the three XR.1.6400 valves for 2 kW on 115 volts, which underloads them, whereas two valves would be overloaded. Experience has shown that one should always work well within the rating of such valves. Their short preheating time does not offset heat losses, because they are in use for full light or check positions, and when a circuit is 'out' it must be at the ready. No rehearsal or transmission lighting change can allow even a minute time lag—the shot would be over. Patching 300 circuits to 96 dimmer channels as at Riverside means that the majority of the latter are likely to be in use.

Mr. J. Stap.—Fluorescent tubes may be prominent in Holland, but they are seldom encountered elsewhere; indeed the statement by Mr. Roos, referred to, was corrected by me in a subsequent article in the same journal.*

The most noticeable thing about the German studios, for example, is the small amount of softlight used, and this is provided by tungsten-filament lamps. Iconoscopes certainly require more light, but the Germans prefer to use contrasty spotlighting. Even with image orthicons, although camera and lamp manufacturers have a strong belief in softlight, the users in Britain and the United States see the matter differently. In any case, there are many times when softlight cannot be allowed to stray and fluorescent lamps make up as fittings which are bulky and difficult to control optically.

Mr. Samson.—The patching system in Riverside I is probably the only remotely controlled one in the world. The lighting supervisors find it easy to work, but it suffers from two drawbacks. The first is an absurd phase layout: laying out to ensure that each of the 4-way hanging bars in the studio has three phases on it to balance the load has produced an arrangement whereby adjacent lanterns in the studio occupy widely separated parts of the lighting control panel proper. The second is limitation of patching choice: one could increase the choice by using 100 contact-servo-operated selectors, but this would be a direct equivalent of 100 contact dimmers supplied to each circuit; the main object of patching is to reduce initial outlay.

I was informed when visiting the United States that a colour temperature of 2900° ± 300° K was permissible for flesh tones in colour television. The practice seemed to be to set the camera response initially, using three girls as models; all other effect was obtained by colour in setting and costume or even lighting, but not by distortion of camera response.

I agree with Mr. Samson on the use of artist-lighting supervisors to operate the television control, for this man should be painting a picture with light—an intimate process which cannot admit of an intermediary. All lighting control design must be directed to this end, and engineering considerations should be completely subservient. A real artist will avoid the trap of fidgeting referred to by Mr. Eckersley.

Mr. Sharp.—The control process in television and theatre lighting is part of a live show and subject to all the advantages and drawbacks this brings; consequently, recording for completely automatic operation has no place. Improvisation and modification continue up to, and sometimes during, the first performance. In television there will be no repeats; in theatre the show may run and switchboard operation become easy—it is the rehearsal state of flux which makes the biggest demands on control and operator. Since an operator must always be on duty at the control to cover the slips and inconsistencies to which any live show is liable, one could not justify the purchase of full automation.

Son et Lumière is a different case: the sound is recorded and thus the lighting should be. Unfortunately, the capital available for these shows in this country is already too limited to allow really adequate lighting, let alone control elaboration. A short season at the mercy of the weather is not very encouraging.

Mr. Gostt.—I understand that B.B.C. candidates are expected to have had 4 years' experience in television; they then have 6 months' specialist lighting training followed by practical experience as a lighting assistant. Thus, some 6 years pass before one can become a full lighting supervisor. The B.B.C. training standards are beyond question, but the same cannot be said for all who are 'in television'.

* BENTHAM, FREDERICK: 'Television Lighting Control', *International Lighting Review*, 1957, **4**, p. 136.

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AN EXPERIMENTAL APPROACH TO THE COOLING OF TRANSFORMER COILS BY NATURAL CONVECTION

By E. D. TAYLOR, M.Sc., B. BERGER, B.Sc.(Eng.), and B. E. WESTERN, B.Sc., Associate Members.

(*The paper was first received 7th June, and in revised form 25th October*, 1957.)

SUMMARY

The paper describes the experimental work and results of a study of the heat-transfer properties of cooling ducts in transformer coils under natural convection. The data for layer windings of various vertical duct sizes and coil heights are generalized in terms of empirical copper-to-oil temperature gradients. Consideration of the vertical coil leads to a method of treating an assembly of disc coils individually, and it is shown that the individual disc-coil variables are represented conveniently by a correlation type of formula. Finally, it is indicated how the data may be used to predict the hot-spot temperature of a transformer in service.

LIST OF PRINCIPAL SYMBOLS

A = Area.
c = Specific heat of unit mass.
f_c = Convection coefficient or heat-transfer coefficient.
g = Acceleration due to gravity.
h = Height.
k = Thermal conductivity.
l = A linear dimension, usually a characteristic dimension as used in dimensional analysis.
N = Numerical constant.
n, p = Indices.
Q = Quantity of heat per unit area per unit time.
α = Coefficient of thermal expansion.
Θ = General symbol of temperature.
θ = General symbol of temperature difference.
μ = Absolute viscosity.
ν = Kinematic viscosity = μ/ρ.
ρ = Density.
Θ_a = Ambient temperature.
${}_c\Theta_{max}$ = Winding hot-spot temperature.
${}_c\Theta_m$, ${}_c\theta_m$ = Mean winding temperature, rise in mean winding temperature. ${}_c\Theta_m = {}_c\theta_m + \Theta_a$.
${}_0\Theta_m$, ${}_0\theta_m$ = Effective mean oil temperature, rise in effective mean oil temperature.
${}_g\theta_m$ = Mean winding temperature gradient = ${}_c\theta_m - {}_0\theta_m$.
${}_0\Theta_u$, ${}_0\theta_u$ = Top oil temperature, rise in top oil temperatures.
${}_c\Theta_h$, ${}_c\theta_h$ = Copper temperature, rise in copper temperature, at any height h up the winding.
${}_0\Theta_h$, ${}_0\theta_h$ = Duct oil temperature, rise in duct oil temperature, at any height h.

Groups.

M = Natural convection modulus (dimensional) = $\dfrac{\alpha g c \rho}{\mu k}$

N = Nusselt number = $\dfrac{Ql}{k\theta}$

P = Prandtl number = $\dfrac{c\mu}{k}$

G = Grashof number = $\dfrac{\alpha g \theta l^3 \rho^2}{\mu^2}$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
The authors are with C. A. Parsons and Co. Ltd.

(1) INTRODUCTION

The cooling of transformer coils is in principle a simple mechanism, and is performed by passing a cooling liquid through ducts, the driving force being either natural or forced convection. The fluid in turn exchanges heat with its surroundings via some other exchange arrangement, such as air-cooled pipes or a water cooler. In this heat-exchange mechanism the electrical engineer focuses his interest on the highest temperature of the transformer, and this point has received a great deal of study. There are accepted formulae, differing somewhat in different countries, which give the hottest spot in a winding in terms of certain other temperatures, but which take no account of winding and duct dimensions or of liquid parameters. There appears to be no quantitative information on the effect of these, and little consideration has been given to the heat-transfer mechanism as a whole. There is thus a need for detailed experimental work, a point clearly made in Coleman's review of published transformer-temperature information.[1]

The problem proves to be complicated and empirical. For example, an assembly of horizontal disc coils can vary in the following parameters: height of the cooling duct; radial depth of the coil; number of turns per coil; thickness of insulation between turns; total number of coils; radial dimension of the surrounding vertical duct. The attempt to produce a comprehensive temperature formula which will include all these variables is likely to be unprofitable, and this is also true for the simpler problem of the layer winding. However, it is the aim of the paper to show that experimental work does lead to an understanding and evaluation of the effects of the various parameters. To assist in this there is value in considering the problem as a general one in heat transfer. This method of approach has been used by Davis,[2] to compare the cooling properties of oils, and by Montsinger.[3] In this approach, an idealized picture is formed; each transformer winding is considered separately and treated as if it were a solid vertical cylinder immersed in an infinite volume of fluid of constant bulk temperature. The heat transfer depends on the shape of the cylinder and on the physical properties of the surrounding fluid. The mechanism of natural convection can be represented by an equation usually derived dimensionally,[4] namely

$$\left(\frac{Ql}{k\theta}\right) = N_1\left(\frac{\alpha g \theta c l^3 \rho^2}{k\mu}\right)^p \quad . \quad . \quad . \quad . \quad (1)$$

or, in the form given in heat-transfer literature,

$$\mathrm{N} = N_1(GP)^p$$

in which N_1 and p are constants to be determined experimentally. The equation is well known to engineers in its simplest form, when applied to a particular piece of apparatus,

$$\theta = N_2 Q^n \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $n = 1/(1 + p)$ and is approximately $0{\cdot}8$.

Eqn. (1), with particular values of p and N_1, theoretically holds only for bodies which possess the same geometrical shape (or, more strictly, the same flow-pattern shape), such that they may

be described by just one linear dimension, l. In practice, however, quite large differences in shape result in only minor errors in correlation. The variables in eqn. (1), for a continuous cylindrical oil-immersed transformer winding concentrically surrounded by an annular duct, are the energy input, Q, the rise of the mean winding temperature above the mean oil temperature, θ, the physical constants of the oil, α, ρ, k, μ, and the height of the cylinder, l.

The relevance of this formula to transformers is that results of experimental work can be compared with those of other experimenters working in quite different fields; it allows other operating conditions to be estimated; it makes a fairly precise statement of the indices attached to each parameter; it gives a method of studying the horizontal-duct variables. On the other hand, this formula is inadequate for detailed study of local temperature rises and convection coefficients and it omits the heat transfer by the fluid to the ambient.

(2) THE TRANSFORMER, THE OIL AND THE TANK

There are two important experimental observations which condition any data that can be presented on this subject.

The first concerns the exit conditions of a vertical duct. Around and above the exit the temperature of the oil is closely uniform (the top oil temperature), except for a local hotter oil stream ascending from the heated surface which dissipates itself in the top bulk oil; the remaining oil in the top few inches of such a duct is only in very slow motion and takes up a temperature close to that of the top bulk oil.

The second observation concerns the difference in temperature between the inlet oil to a duct and the top oil temperature. For a given coil, duct and power input this value is mainly determined by the external heat-transfer conditions; different relative amounts of cooling at top and bottom of the same tank or the use of a local heat exchanger can affect it substantially. Fig. 1 illustrates this: a simplified 1 ft layer coil is shown in two different positions below the surface of the same tank but with almost the same power inputs. The oil temperatures within the duct and the copper-to-oil gradients are seen to be different in the two examples. The copper temperatures, as it happens, are nearly the same. The difference between the two examples is that, in the second, more oil and a larger area of tank are involved so that the top oil temperature can be lower.

The significance of this is that, since the copper temperatures are determined in relation to the local oil temperatures in terms of some appropriate convection coefficient, it becomes impossible to define copper-temperature distribution in terms of power input and coil geometry only. The results given in the paper demonstrate, however, that the values of convection coefficient or of gradient are of general application, so that, once the oil distribution is known, so also is the copper distribution. This is of distinct advantage when the disc winding is analysed, for it then appears that the height of the stack of coils or the number of coils need not be considered as one of the variables, provided that the oil-temperature distribution is known. The disc coils, individually and as a whole, must adjust themselves to the local oil conditions, so that experimentally it is legitimate to consider in detail the individual coil or the individual horizontal cooling duct.

(3) EXPERIMENTAL APPARATUS

For experimental thermal work on the complicated structure of a transformer, a simplification of apparatus must be accepted. Two basic types of apparatus have been used in this work, one simulating the vertical-layer winding and the other the disc winding.

(3.1) The Vertical-Layer Winding and Vertical Ducts

Coils were constructed 1 ft, 2 ft, 3 ft and 5 ft high consisting of a single layer of bare copper strip $0{\cdot}11$ in $\times$ $0{\cdot}90$ in cross-section wound on an 8 in diameter $\frac{1}{2}$ in thick Bakelite tube with insulation between adjacent turns and spiralled insulating spacers at top and bottom carefully cut to present a smooth cylindrical surface. Within the Bakelite former were baffles which retarded and made precise any internal heat transfer. The coils were concentrically surrounded by other Bakelized-paper tubes to form ducts of various sizes. Connection to the coil was made inside the Bakelite former, and the external leads were of larger cross-section to reduce the local power generated; they were also fitted with small heaters to eliminate thermal conduction from the coil.

Temperatures were measured by copper-constantan thermocouples soldered into tiny holes drilled in the coil turns. On the assumption of cylindrical symmetry they lay in a single vertical line, one in each turn for the 1 ft and 2 ft coils and one in every other turn for the 3 ft and 5 ft coils. The thermocouple leads were taken through the coil former into the centre of the assembly and through the top baffle, thus leaving the couple level with the copper strip. Thermocouples also measured the oil temperatures vertically on the same radial lines as the copper thermocouples, whilst others measured the oil temperatures within the Bakelite former. Careful early subsidiary tests showed that oil temperatures in the duct at any distance greater than $\frac{1}{16}$ in away from the heated surface were almost constant, but that a steep gradient occurred within the $\frac{1}{16}$ in. It was thus considered that a $\frac{1}{8}$ in spaced thermocouple gave the temperature of the neighbouring bulk oil, and this was standard throughout the tests except for the $\frac{1}{8}$ in ducts where $\frac{1}{16}$ in spacing was used. The thermocouples themselves projected through the outer cylinder. When there was no surrounding cylinder—the infinite duct or open coil—the thermocouples were mounted on a frame.

Three of the four sets of this type of assembly, the 1 ft, 3 ft and 5 ft coils, were suspended in a tank, 3 ft 6 in diameter 7 ft high, holding 700 gal of oil and fitted with a distributed water-cooling coil on the inside wall. The fourth assembly, the 2 ft coil, was tested in a 21 in diameter 4 ft high tank containing a chlorinated-diphenyl coolant. All the coils were mounted 9 in below the coolant surface, maintained at a constant level. They were heated by direct current and the readings were taken only under completely steady conditions; the average of three successive sets of readings, 15 min apart, then represented one particular condition.

The copper-temperature readings plotted against height showed a scatter from the mean curve, due to the small potential drop across the finite volume of junction lying in the path of the direct current. In the 3 ft and 5 ft coil assemblies these error potential drops were measured by a preliminary test, whilst for the 2 ft coil the wires of each couple were so arranged that no correction was necessary. The average coil temperature was also frequently checked by resistance, and agreement with the mean of the distribution curve was always better than $\pm 2°$C.

(3.2) The Horizontal Ducts between Disc Coils

It is more useful to think of the cooling properties of a duct than of the dissipating properties of a coil. Thus any pair of successive coils of a stack of disc coils forming a winding operate under almost identical conditions, except at the very top and bottom of the winding. The fluid in the horizontal duct between them is thus cooling two parallel surfaces possessing the same temperature conditions, except that different quantities of heat are transferred at the two surfaces, that by the lower surface being greater than that by the top surface. Such conditions can

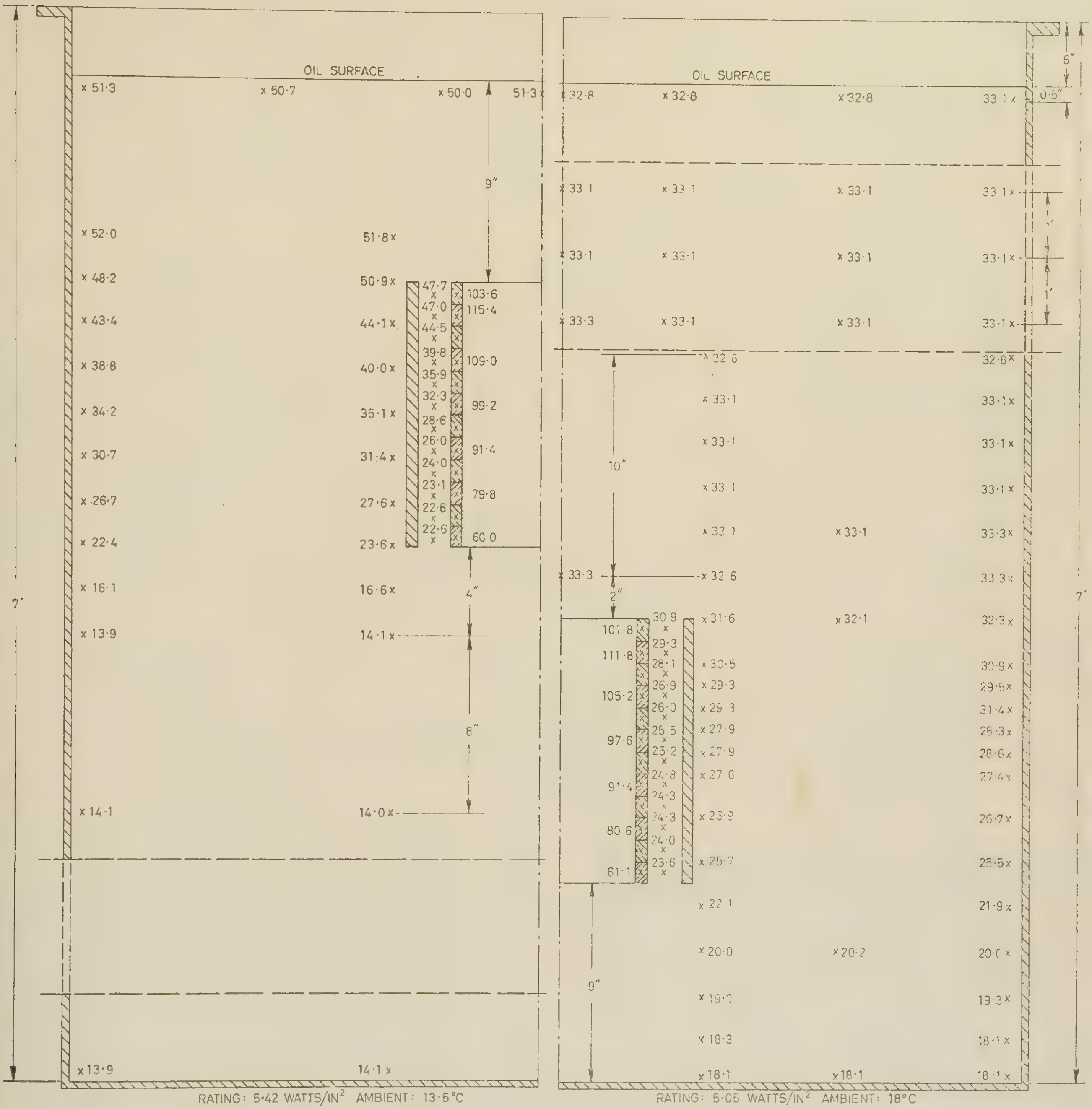

Fig. 1.—Influence on temperature distribution of changing effective tank cooling area.

be set up in an easily adjustable equipment by forming two coils with an intermediate duct, of which the top of the upper coil and the bottom of the lower coil are thermally lagged and in which the top coil can be controlled in sections independently of the bottom coil to give both the same mean temperature and temperature distribution.

A simplified diagram of the apparatus is shown in Fig. 2. For symmetry and simplicity of control the coils were designed linearly instead of concentrically. To decrease the loss on the vertical faces in relation to the horizontal faces, $\frac{1}{8}$in extra thickness of insulation was allowed. To produce maximum gradients within the coil, thin copper strip, $0{\cdot}34\,\text{in} \times 0{\cdot}11\,\text{in}$, with 20-mil paper insulation was used. The coil length was 2 ft for each, the strip being zigzagged and laid in $\frac{1}{2}$ in Bakelite, which acted as the resistance to vertical heat flow. The horizontal separation was fixed by four sets of narrow spacers. The whole assembly was suspended in a large tank of oil. Copper/Eureka thermocouples of 40s.w.g. wire were inserted in holes drilled in the coppers, with the leads taken between the copper and the Bakelite for 2in before passing through the Bakelite. Other thermocouples gave a series of oil temperatures inside and outside the duct.

This apparatus was made in three coil widths, 1 in, 3 in, $4\frac{1}{2}$ in, and in each case the separation was varied through the range $\frac{1}{16}$in, $\frac{1}{8}$in, $\frac{1}{4}$in, $\frac{1}{2}$in. The total number of oil and copper thermocouples in each assembly was between 30 and 46.

The measurements were made under steady conditions as for

the vertical ducts. The major errors for which allowance had to be made in the data were:

(*a*) Heat loss by the backing insulation and at the ends of the long coils. This was estimated both by suitable thermocouples and by dummy runs with zero duct.

(*b*) Errors due to the inability to reproduce identical temperature distributions in the top and bottom coils.

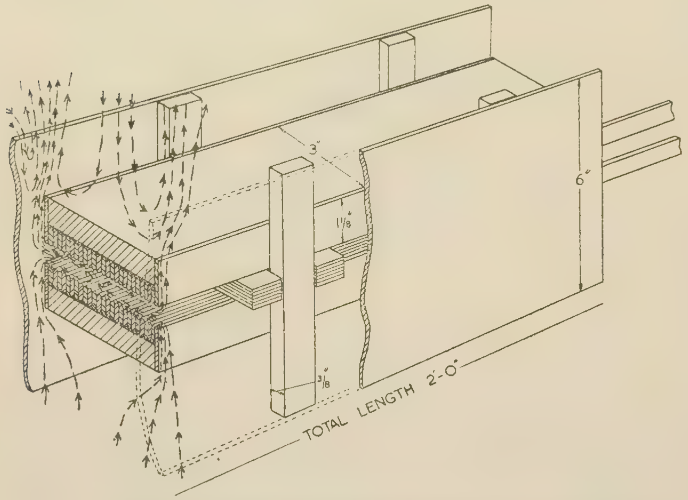

Fig. 2.—Section of the disc-coil model showing the oil flow pattern.

A more serious criticism is that the results do not truly represent the loss for a complete coil. In order to check this, an entirely separate apparatus was constructed of five similar 2 ft long 3 in wide coils, but without insulated backings, and the middle one of these was measured in a similar manner for heat input, temperature and gradients. The results of the comparison between the experimental arrangements were so close that it appeared clear that the original experimental set-up was, in fact, a fair representation of the conditions. This is dealt with in more detail in Section 5.

(4) REPRESENTATION OF EXPERIMENTAL RESULTS FOR VERTICAL COILS

The main results are set out in Figs. 3–5 in the form of three sets of curves representing the distribution with height of the oil temperatures, copper temperatures and convection coefficients. Each set comprises three further sets of curves representing coils 1 ft, 3 ft and 5 ft high, while these in their turn contain curves illustrating the effect of different duct sizes. The curves are selected from about three times their number and so consistent are the results that these may be taken as representative. (In the subsequent derived curves, all results are taken into account.) The three subdivisions of oil temperatures, copper temperatures and heat-transfer coefficients will be discussed in turn, and thereafter it will be shown that the results can be generalized by considering copper-to-oil gradients.

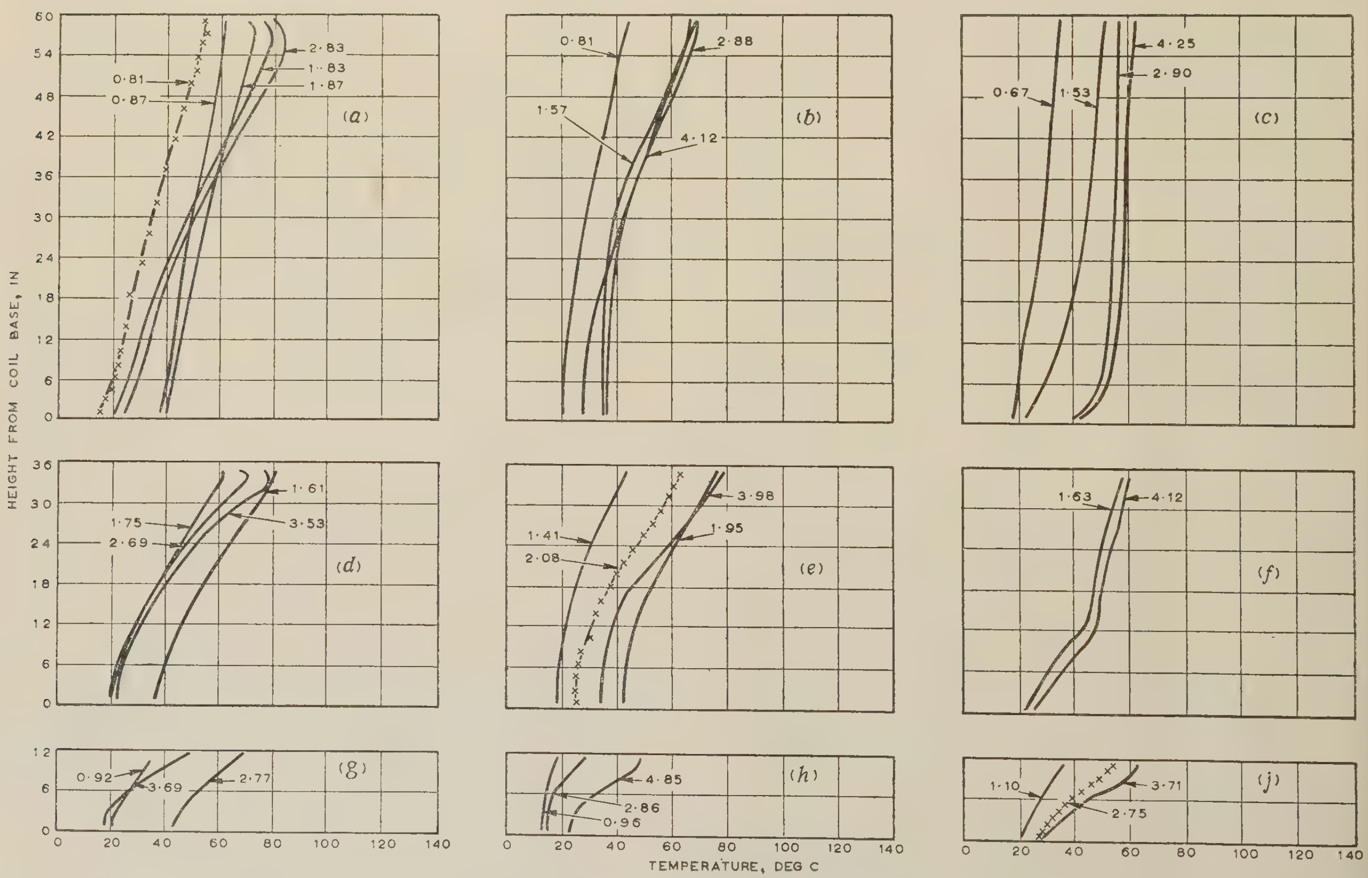

Fig. 3.—Oil-temperature distributions for 1 ft, 3 ft and 5 ft coils: natural convection.

Numbers on curves denote heat dissipation of the copper surface exposed to the oil, in watts/in².

(*a*) 5 ft coil, ⅛ in duct.
(*b*) 5 ft coil, ¼ in duct.
(*c*) 5 ft open coil.
(*d*) 3 ft coil, ⅛ in duct.
(*e*) 3 ft coil, ¼ in duct.
(*f*) 3 ft open coil.
(*g*) 1 ft coil, ⅛ in duct.
(*h*) 1 ft coil, ¼ in duct.
(*j*) 1 ft open coil.

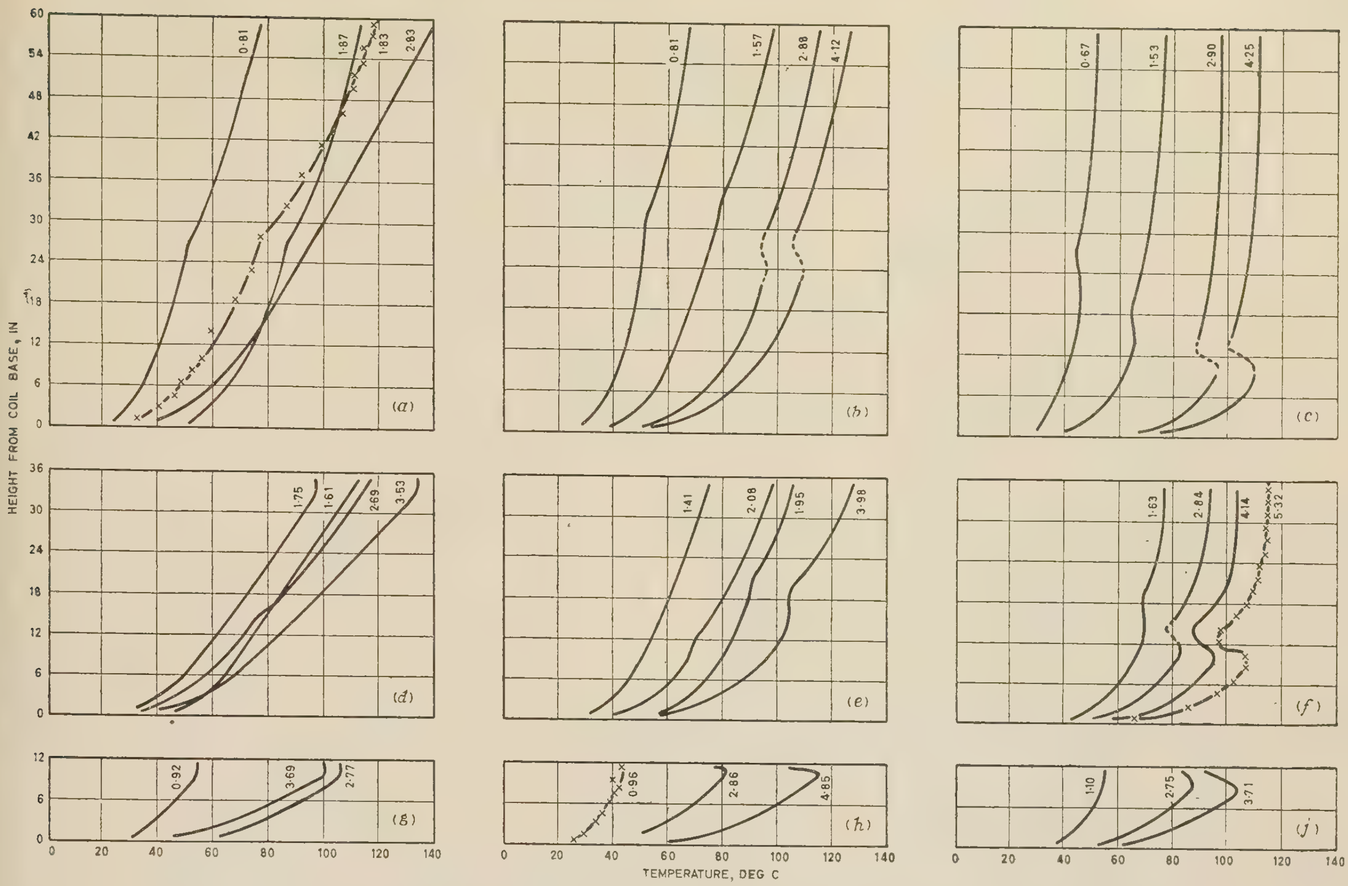

Fig. 4.—Copper-temperature distributions for 1 ft, 3 ft and 5 ft coils: natural convection in transformer oil.

Numbers on curves denote heat dissipation of the copper surface exposed to the oil in] watts/in².

(*a*) 5 ft coil, $\frac{1}{8}$ in duct.
(*b*) 5 ft coil, $\frac{1}{4}$ in duct.
(*c*) 5 ft open coil.
(*d*) 3 ft coil, $\frac{1}{8}$ in duct.
(*e*) 3 ft coil, $\frac{1}{4}$ in duct.
(*f*) 3 ft open coil.
(*g*) 1 ft coil, $\frac{1}{8}$ in duct.
(*h*) 1 ft coil, $\frac{1}{4}$ in duct.
(*j*) 1 ft open coil.

(4.1) The Distribution of Oil Temperature

It has been pointed out in Section 2 that the difference between top and bottom oil temperature of a vertical duct is mainly determined by conditions external to the duct. On the other hand, the actual shape of the temperature-distribution curve is determined partly by the duct itself. When the coil is open to the tank, local external oil conditions play a bigger part in determining the distribution than when the coil is separated from them by a barrier.

Examination of Fig. 3 shows that the oil-temperature distribution depends markedly on whether a duct is present and to a smaller extent on the size of the duct. Thus, the $\frac{1}{8}$ in and $\frac{1}{4}$ in ducts for 3 ft and 5 ft coils give parabolic distributions concave to the temperature axis (the curve for the $\frac{1}{8}$ in duct is more closely linear), while the infinite duct gives parabolic distributions convex to the temperature axis. It is of interest that Nolen[5] shows distributions of similar shape for open coils. The coil distributions of the 1 ft coil exhibit the same basic shape for all duct sizes.

To take into account the differences in oil-temperature rises and coil height, the forms of these curves can be generalized for dissipations less than 1 watt/in² by expressing the percentage oil-temperature rise in terms of percentage height (Table 1). The accuracy is $\pm 10\%$ of the total oil-temperature rise.

Table 1

PERCENTAGE OIL-TEMPERATURE RISE AS A FUNCTION OF PERCENTAGE COIL HEIGHT FOR DISSIPATIONS LESS THAN 1 WATT/IN²

Percentage height	Percentage oil-temperature rise					
	$\frac{1}{8}$ in duct		$\frac{1}{4}$ in duct		Open coil	
	1 ft coil	5 ft coil	1 ft coil	5 ft coil	1 ft coil	5 ft coil
20	6	24	4	8	15	25
40	30	41	13	26	36	54
60	56	61	38	49	58	75
80	81	83	66	75	81	87

(4.2) Distribution of Copper Temperature

The distribution curves (Fig. 4) for the 3 ft and 5 ft coils can be divided into three parts. Over a portion about 1 ft high at the entrance of the duct there is a rapid rise of temperature, whilst over the upper part of the coil the rate of rise of temperature is smaller and fairly constant. These two zones are separated by a change-over region characterized by an irregularity. The shape and extent of this region depend upon the duct size and the coil dissipation. For example, the irregularity is most pronounced for the open coil and its position moves towards the bottom of the coil as the dissipation is increased. On the other hand, for the $\frac{1}{8}$ in duct the change-over region has almost disappeared. Thus the copper-temperature distribution curves all form part of a distinct pattern. The 5 ft coil shows that it can be considered as a 3 ft coil with an extended upper section, and the 1 ft coil distribution shows itself as the initial portion interrupted by an

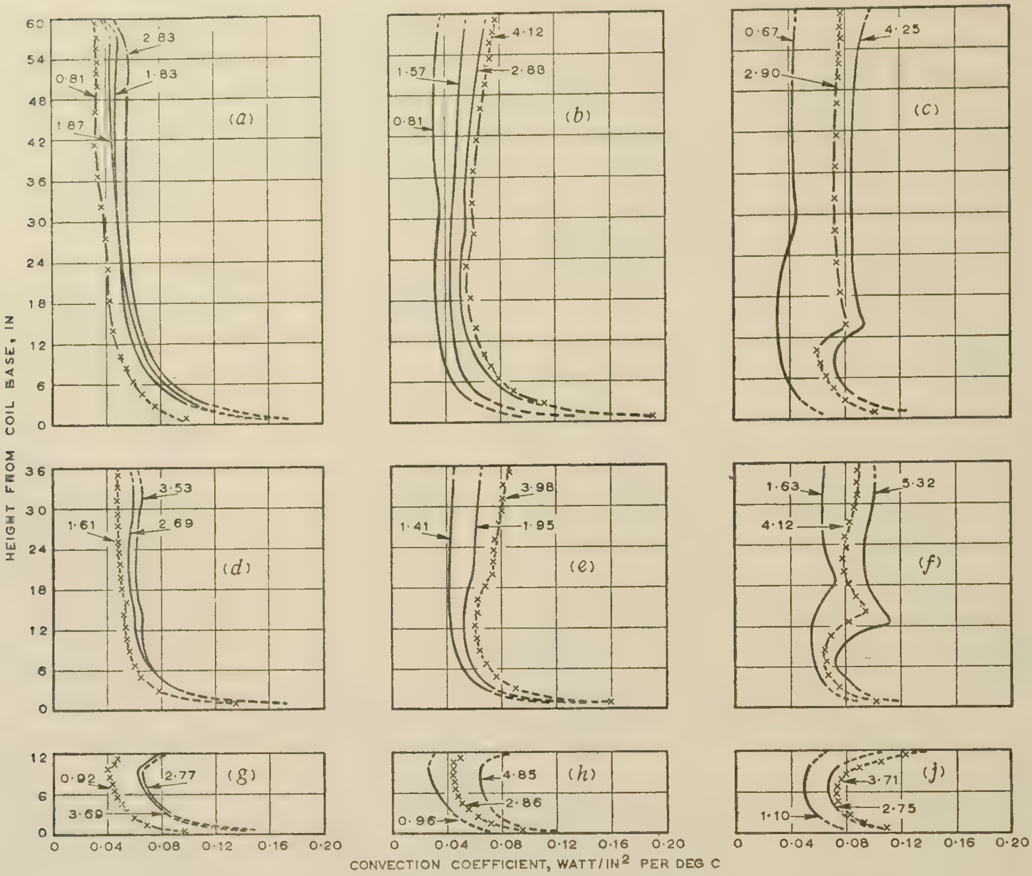

Fig. 5.—Convection-coefficient distributions for 1 ft, 3 ft and 5 ft coils: natural convection in transformer oil.

Numbers on curves denote heat dissipation of the copper surface exposed to the oil in watts/in².

(a) 5 ft coil, ⅛ in duct.
(b) 5 ft coil, ¼ in duct.
(c) 5 ft open coil.
(d) 3 ft coil, ⅛ in duct.
(e) 3 ft coil, ¼ in duct.
(f) 3 ft open coil.
(g) 1 ft coil, ⅛ in duct.
(h) 1 ft coil, ¼ in duct.
(j) 1 ft open coil.

end effect. This leads to a fairly reliable basis of extrapolation for coils of larger dimensions.

The maximum copper temperature for the 3 ft and 5 ft coils occurs at the very top of the duct, except for a few ⅛ in duct cases; for the 1 ft coil there is a distinct exit effect resulting in a reduction in temperature of the upper turns.

(4.3) Distribution of Convection Coefficient

If Q denotes the average per unit area dissipation into the duct, i.e. the portion of the total loss dissipated into the duct divided by the coil surface area, the convection coefficient at height h is given by

$$f_{ch} = \frac{Q\left(\dfrac{1 + 0{\cdot}004\,{}_c\Theta_h}{1 + 0{\cdot}004\,{}_c\Theta_m}\right)}{{}_c\Theta_h - {}_0\Theta_h}$$

where 0·004 represents the temperature coefficient of resistance of copper.

Distributions of convection coefficient can therefore be derived (Fig. 5). It follows from the formula that the convection-coefficient distribution is approximately the mirror image of the local oil-to-copper gradient distribution with height. The coefficients are large and indeterminate at the very bottom, but over the greater part of the length of all the coils with ducts, they lie between well-defined limits of 0·03 and 0·08 watt/in² per deg C for inputs between 0·5 and 5 watt/in²; the open coils, while consistent among themselves, show a big discontinuity but with similar limits to the values. Generally, the greater the input and the higher the operating temperatures, the greater is the convection coefficient. The distributions again show that the 5 ft coil may be considered as a 3 ft coil extended over the upper section.

(4.4) Copper-to-Oil Temperature Gradient

In any horizontal plane, at whatever height up the coil it is considered, the oil has a constant temperature to within about $\frac{1}{16}$ in from the heated surface. Between this bulk oil and the copper surface is a temperature difference which is known as the gradient. The oil in this zone adjacent to the surface moves rapidly (several centimetres per second) compared with the remainder in the duct. It would appear that this film of ascending oil at the heated surface is the major carrier of heat from the coil, and its velocity is therefore inversely related to the copper-to-oil temperature gradient. It is logical to think that restricting the duct to a dimension comparable to the film width would raise the gradient, whilst higher duct-oil temperatures, at which the oil is thinner, would reduce it. Above all, it seems reasonable to expect that the gradient is independent of coil height.

The foregoing suggests that the evaluation of copper-to-oil gradients at a given duct-oil temperature is likely to present a composite picture. Thus, from the distribution curve, one can choose a certain oil temperature and for each duct in turn, where that oil temperature occurs, determine values of gradient and true local power input. Sufficient points accrue from the three coil sizes to construct a well-defined curve. The points turn out to be most consistent, except when the height at which the chosen

duct-oil temperature occurs is less than about 10% of the total height, i.e. near the entrance. Over this lowest region the gradients are always appreciably less than those over the remainder of the coil.

The data when treated in the above way yield a set of mean gradient curves, four of which, namely the $\frac{1}{4}$ in and open coil 30° C and 60° C curves, are shown in Fig. 6. That the gradients are independent of the coil height is thus established, and they

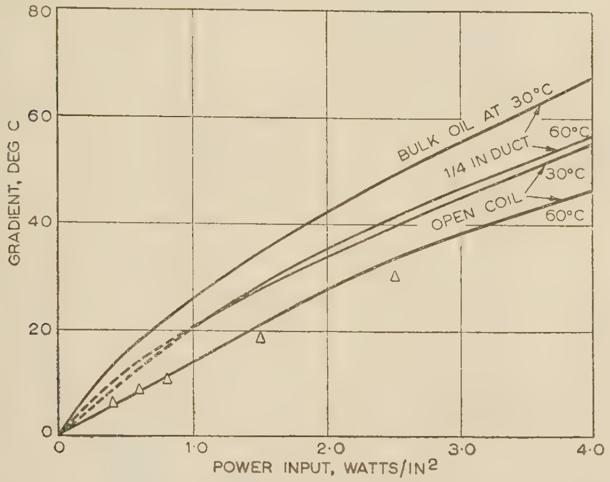

Fig. 6.—Relation between copper-to-oil gradient for any coil height (ignoring entrance conditions).

△ Gradients given in Reference 11 for 60° C oil.

have definite values which may be applied to any coil height, power input, oil temperature and duct size. Moreover, the difference between various sizes of vertical cooling duct and the influence of oil temperature now becomes clear. Thus, for example, at a given oil temperature, although the gradient falls as the duct is widened, this improvement can be offset or even reversed by lowering the oil temperature. There is little difference, for instance, between a $\frac{1}{4}$ in duct operated at 60° C and an open coil operated at 30° C.

As a layer winding is ascended the effects on the gradient of increased oil temperature and rise in dissipation tend to neutralize each other, so as to give a more nearly constant gradient/height distribution in the upper part of the transformer. This is clearly shown by the 3 ft and 5 ft convection-coefficient distribution curves.

The curves for the $\frac{1}{8}$ in duct, which, like those for the $\frac{1}{2}$ in duct, are not shown in Fig. 6 for the sake of clarity, actually lie within the $\frac{1}{4}$ in band. This arises because the oil thermocouples in the $\frac{1}{8}$ in duct were $\frac{1}{16}$ in from the coil surface, whilst the separation was $\frac{1}{8}$ in for all the other duct sizes. The $\frac{1}{8}$ in duct gradient values are therefore lower than their comparable values.

These mean gradients, as already mentioned, do not obtain in the bottom 10% of the winding; it turns out that at the bottom they are independent of oil temperature, and for the 3 ft and 5 ft coils are best expressed as a function of percentage coil height. The corresponding 1 ft coil bottom gradients are somewhat lower.

(4.5) Results for a Chlorinated-Diphenyl Coolant

Similar sets of results were obtained using a coolant of the chlorinated-diphenyl type (of characteristics given in Fig. 13), in a smaller tank and for the 2 ft coil with $\frac{1}{4}$ in and infinite ducts. The temperature distributions bore patterns similar to those shown for the oil experiments, even to the details of the points of inflection in the copper-temperature distribution, so

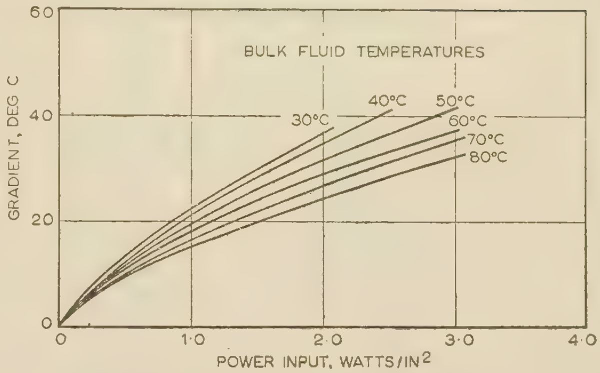

Fig. 7.—Relation between copper-to-fluid gradient and power input for a chlorinated-diphenyl coolant.

2 ft coil: $\frac{1}{4}$ in duct and open coil.

that only the final gradients need to be shown for this fluid in Fig. 7. The result, that the gradients are independent of duct size, is not entirely unexpected. Assuming that the major agency of heat removal is a narrow ascending film, it follows that the effect of the duct is of secondary importance, provided that the duct is wider than the film. It would appear that the smaller the density of the fluid, the less constrained is it to move in a narrow film and hence the greater is the importance of the ducts. The comparison with oil as a heat-transfer medium is obtained directly from the gradient curves, Figs. 6 and 7.

(4.6) The Correlation Curve

A single representation of the temperature distributions for the whole coil requires that the copper and oil temperatures shall be represented by averages. When these, together with values of the appropriate physical constants, power input and coil height, are inserted into eqn. (2), the graph of Fig. 8 is obtained. The mean lines for the various coil heights have approximately the same slope, i.e. in eqn. (1) $p \simeq 0{\cdot}29$. The results for the 1 ft and 2 ft coils over the range of GP $= 9{\cdot}7$ to $11{\cdot}2$ are close to those usually accepted for the general convection problem, and although they are consistent beyond this region, none the less, considering the widely separated curves of Saunders and of Touloukian[4] and the scatter of the authors' points, these curves can have little value in providing the designer with precise data. On the other hand, over the well-substantiated part of the curve below GP $= 9{\cdot}5$ it has a value in estimating what might be expected under special conditions or with some other coolant. Unfortunately, most transformer temperature data lie outside this range.

All the data of the vertical layer-type windings have now been analysed and their interrelations can now be summarized. The heat exchange is in two parts: that between the heat generator and the fluid, and that between the fluid and the surroundings. The distinction between this and the usual observation that the heat transfer takes place between a static body and a cooling fluid is important. In the first place, for a given energy input the temperature of the heated body depends as much on the fluid-to-ambient convection coefficient as it does on the body-to-fluid coefficient. The highest and lowest temperatures of the fluid, however, depend mainly upon the fluid-to-ambient heat-transfer conditions; these include the geometry, position and external condition of the tank, the heat to be dissipated, the physical constants of the fluid, etc. For example, the top and bottom fluid temperatures of a transformer would be greater if filled with a gas instead of oil, despite equal external cooling conditions and heat generation. Secondly, the temperature rise and density

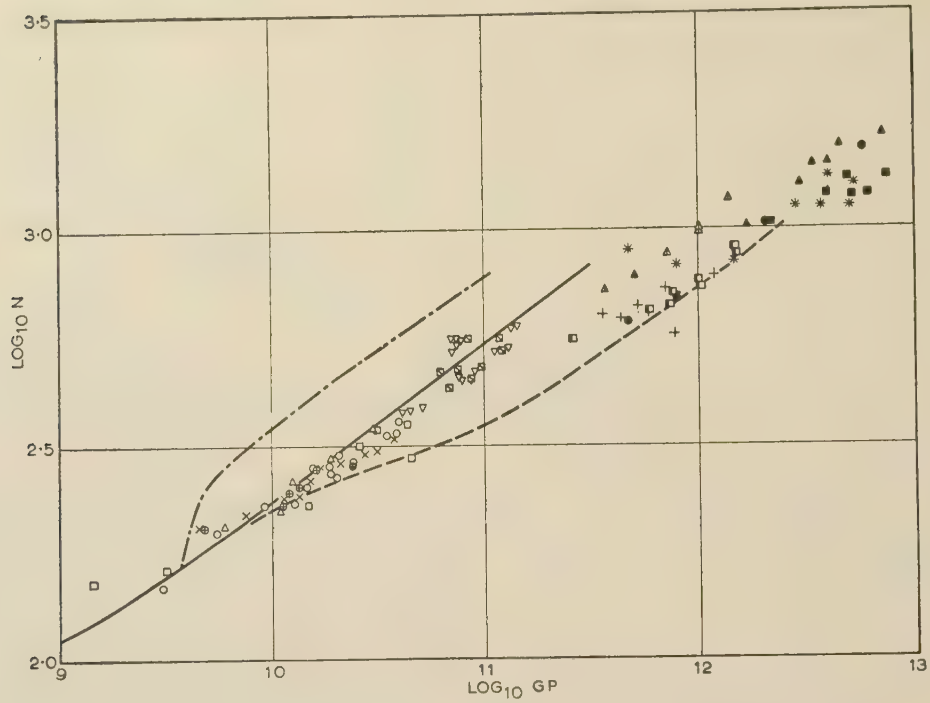

Fig. 8.—Correlation of results for vertical layer-type windings: natural convection in transformer oil and in a chlorinated-diphenyl coolant.

——— Standard correlation curve for vertical surfaces.[4]
–·–·– Touloukian's results: 3 in diameter vertical cylinder in water.
–—– Saunder's results: vertical plane surface in water.

		1 ft coil (oil)	2 ft coil (chlorinated-diphenyl)	3 ft coil (oil)	5 ft coil (oil)
$\frac{1}{8}$ in duct	..	×		+	*
$\frac{1}{4}$ in duct	..	□	⧄	◧	■
$\frac{1}{2}$ in duct	..	○			●
1 in duct	..	⊕			
Open coil	..	△	▽	◭	▲

determine the overall pressure head controlling the thermosyphon flow. Now the rate of flow for a given head and a fixed route of flow is inversely proportional to the viscosity. In practice, coolants have physical constants of which only the viscosity varies appreciably with temperature, and a reduction in the viscosity increases both the fluid-to-surroundings and the body-to-fluid convection coefficients. It follows that, for a given power input, the gradients body-to-fluid and fluid-to-surroundings will fall as the ambient temperature rises. For example, of two identical transformers, equally loaded but with different ambient temperatures, the one with the higher ambient temperature will operate with the smaller fluid temperature rise.

(5) REPRESENTATION OF DATA FOR THE HORIZONTAL DUCTS

Typical curves of the mean temperature rise of the partly insulated horizontal coils above the inlet oil to the duct are shown in the full lines of Fig. 9, in terms of the total power input to the duct, duct size and inlet oil temperature. The dotted lines of this diagram were obtained on the complete coils referred to at the end of Section 3.2; clearly, the cooling ability of the individual duct corresponds closely to the heat dissipation of the individual coil. The duct-oil temperatures are too complex to warrant detailed discussion and are no more relevant than the local hot oil stream temperatures of the layer coils. However, one set of curves showing mean oil temperature (average of five readings at mid-duct height) is of interest (Fig. 10); these curves show an abrupt change of slope at some critical oil temperature, that at which the oil viscosity is sufficiently low to permit a flow pattern that sweeps the duct.

The overall data can be correlated in a similar manner to that described for the vertical coils. Here, the characteristic dimension is the duct height, while the oil temperature is that of the oil entering the duct. All the points now fall on the three well-defined curves of Fig. 11; at the higher values of abscissae they tend to have the same slope as the standard correlation curve, whilst at the lower end it was not possible to define them with precision. Physically, their interpretation lies in a picture at the higher abscissae of two well-separated coils swept by an active convection flow and, at the lower abscissae, of narrowly separated coils losing almost all their heat by conduction, while the steepness of the curve represents a change from one form of heat transfer to the other. Again, any one graph illustrates that, if a particular oil temperature (and thus oil viscosity) and duct size are selected, corresponding to, say, the abscissa of point A, as the oil temperature is raised so as to increase the abscissa to that of point B, there will be a corresponding increase in convection coefficient. This leads to the conception of a complete disc-type winding as a set of individual coils each possessing a convection coefficient within the locus A to B, according to its height, the points A and B themselves being determined by the bottom and top oil conditions and, of course, by the coil and disc dimensions. These curves do not express the most universal relationship, since the coil width was omitted from the correlation, nor are they necessarily applicable to other fluids, but they probably demonstrate in the simplest way the relative cooling abilities of horizontal ducts in oil. The fact that the graphs are

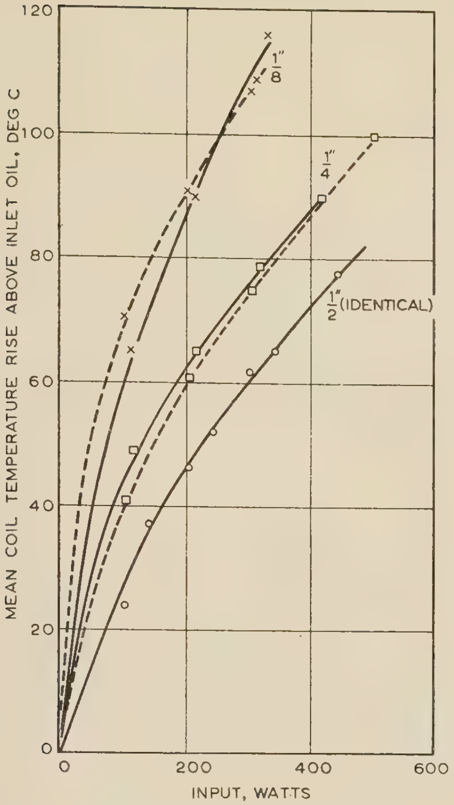

Fig. 9.—Mean temperature rise of the 3 in wide disc-type coils for various horizontal duct heights.

Inlet oil 20° C.
—— Complete coil.
----- Two half-coils.

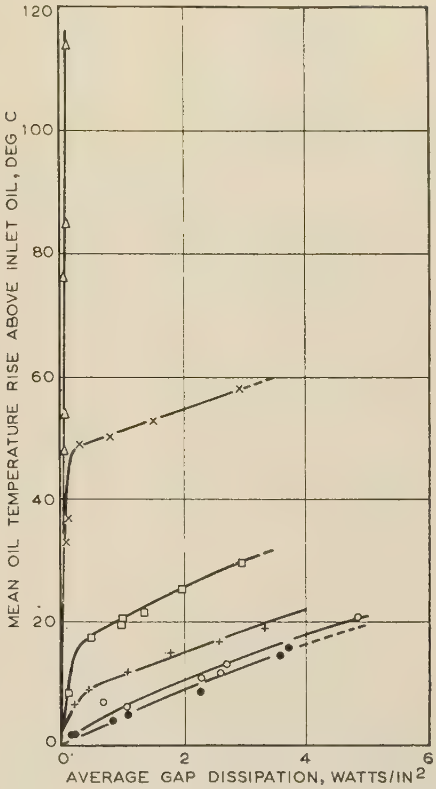

Fig. 10.—Mean duct-oil-temperature rise of the experimental 3 in wide disc-type coils for various horizontal duct heights.

△ $\frac{1}{16}$ in + $\frac{3}{8}$ in
× $\frac{1}{8}$ in ○ $\frac{1}{2}$ in
□ $\frac{1}{4}$ in ● $\frac{3}{4}$ in

curves, as distinct from the straight line of Fig. 8, means that there is no fixed value of p in eqn. (1) or of n in eqn. (2).

It was of interest to analyse the temperature distribution from which the mean temperatures were taken, to obtain the difference between mean copper and maximum copper temperature. This value in a real transformer coil is, of course, dependent on the relative amounts of copper and insulation; the present experimental set-up is so artificial as not to deserve that the absolute values measured should be applied to other conditions. However, the following were approximate rules:

(*a*) The gradients within the coils were almost invariably symmetrical about the centre-line of the coil, except for the $\frac{1}{8}$ in duct where a straight-through flow obtained. The gradients decreased at higher oil temperatures.

(*b*) As the mean copper-temperature/power-input curve is traversed, ${}_c\Theta_{max} - {}_c\Theta_m$ increases almost linearly with distance from the origin.

(*c*) ${}_c\Theta_{max} - {}_c\Theta_m$ is dependent on duct height; for the wider ducts a rough approximation is that the gradient varies inversely as the duct height up to $\frac{1}{2}$ in.

(*d*) ${}_c\Theta_{max} - {}_c\Theta_m$ increases with width of coil but not as fast as proportionately to the width for duct heights of $\frac{1}{4}$ in and over.

(6) RELEVANCE OF THE RESULTS TO COMMERCIAL TRANSFORMERS

(6.1) Methods of Applying the Results

The results have been obtained from laboratory experiments devised to simulate commercial transformer windings. That they give a close picture of the heat-transfer mechanism can scarcely be in doubt, in view of their similarity to the results of other workers.[5, 16, 17] Ultimately, their applicability can only be assessed by using them to predict the copper temperatures of commercial transformer windings, knowing the dimensions, the top and bottom oil temperatures, and power input. If they agree, the results are of wide application. However, treating

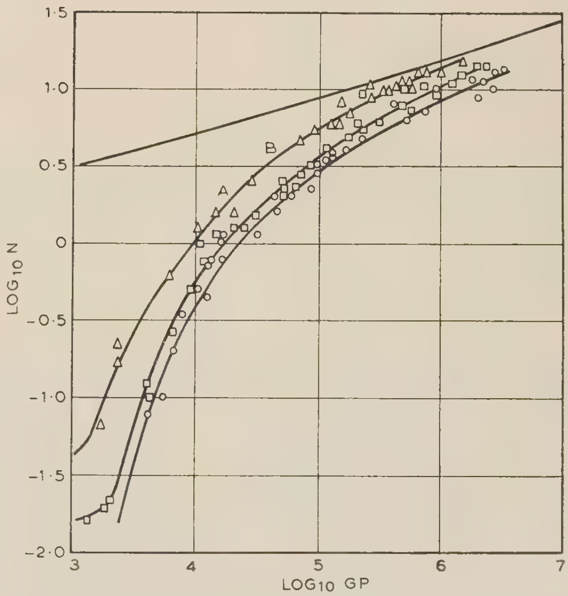

Fig. 11.—Correlation results for horizontal disc-type coils: natural convection in transformer oil.

△ 1 in wide coil. □ 3 in wide coil. ○ $4\frac{1}{2}$ in wide coil.

only one or two transformers in detail is not convincing (and indeed a single example giving an answer to within 1° C is most unconvincing); rather is it necessary to analyse many transformers of different physical sizes and ratings.

The authors have attempted two procedures. The first is to obtain mean copper temperatures from the experimental convection coefficients, measured losses and area of the exposed windings. The second, and more satisfactory, is to determine the copper-temperature distribution in terms of the oil-temperature distribution by using the gradient data, the oil-temperature distribution being found from Table 1. It is important to make allowance for the paper insulation by adding an appropriate temperature drop to the gradient values of Fig. 6. The procedure is given in Reference 4.

In several examples of straightforward layer-type windings the predicted mean temperatures agree with the measured values to within $\pm 10\%$. One of these was a prototype multi-layer winding for a 120 MVA 275 kV transformer on which detailed measurements were possible, which corroborated the oil-temperature distributions and the dependence of the individual duct on conditions external to it.

(6.2) Hot-Spot Temperature Relations

The fundamental parameter of the life of a transformer winding is held to be the hot-spot temperature. It cannot be measured directly, so that empirical formulae[6, 8] have been proposed which relate it to other temperatures that can be measured. As these formulae differ one from another it is natural to inquire whether the data of the present paper can help to assess their validity by examining them as they apply to the layer configuration.

The formulae fall into two types:

(*a*) An arbitrary temperature rise based on experience is added to the mean copper temperature.

(*b*) The hot-spot is taken to occur adjacent to the hottest oil and is expressed as the sum of the highest oil temperature and the copper-to-oil gradient at the hot-spot.

To obtain a simple expression in terms of temperatures which can be measured whilst the transformer is in service, the relation

$$_c\Theta_{max} = {}_0\Theta_u + N_\beta\, {}_g\theta_m$$

is favoured.

Since the mean winding gradient, $_g\theta_m$, depends upon the mean oil temperature, which cannot be measured directly, a further temperature relation must be postulated, e.g. that the oil rise is linear (Great Britain) or parabolic (The Netherlands)[5, 7] with height, or that

$$_0\theta_m/{}_0\theta_u = N_\alpha = 0{\cdot}85 \text{ for natural convection.}^6$$

Type (*a*) is bound to be true within certain specified values of ducts and ratings. A study shows that, for ducts of $\frac{1}{4}$ in and upwards and for dissipation less than 0·5 watt/in², the difference between maximum and mean copper temperatures did not exceed 10° C. The oil temperature itself had only a secondary effect.

For the type (*b*) formula, the experiments show that the maximum oil temperature occurs at the top of the duct and is only slightly greater than the top oil temperature. Plotting the results to ordinates (maximum copper–outlet oil temperature) and (mean copper–mean oil temperature), as in Fig. 12, the mean value of the empirical constant, N_β, in the formula is unity. Inspection of the convection-coefficient distribution curves (Fig. 5), which are approximately the mirror image of the gradient distribution curves, shows that this is reasonable, even though the gradient is not constant with height.

The work shows that, at least for the layer-type winding, the parabolic oil-temperature shape is true only for the infinite duct and that the linear distribution is probably the best all-round

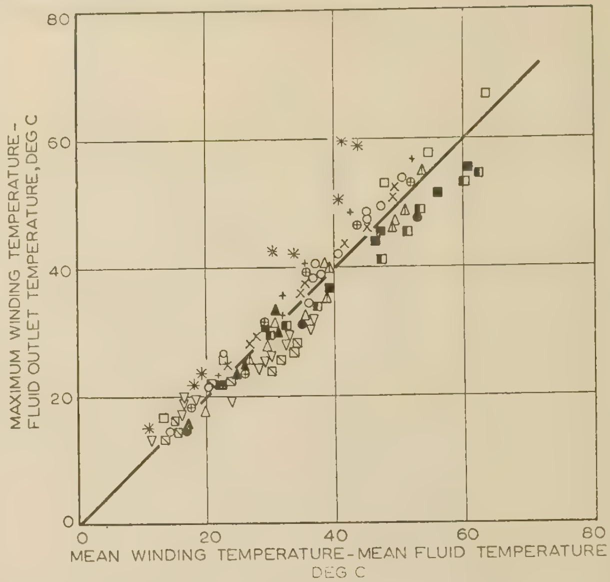

Fig. 12.—Validity of hot-spot formula, $_c\Theta_{max} = {}_0\Theta_u + N_\beta\, {}_g\theta_m$, in relation to the experimental results.

	1 ft coil (oil)	2 ft coil (chlorinated-diphenyl)	3 ft coil (oil)	5 ft coil (oil)
$\frac{1}{8}$ in duct ..	×		+	*
$\frac{1}{4}$ in duct ..	□	⧅	◧	▩
$\frac{1}{2}$ in duct ..	○			●
1 in duct ..	⊕			
Open coil ..	△	▽	⟁	▲

assumption. Because of the artificial ambient conditions in the experiments, Chevalier's expression cannot be verified. The same constant N_α has also been suggested[8] for the ratio of the mean copper rise to the hot-spot rise. If referred to inlet oil instead of to ambient, the copper ratio lies between 0·77 and 0·91 for the open coil and decreases for the narrower ducts. The oil ratio, if referred to inlet oil, is always less than the copper ratio.

The consistency of the gradient curves suggests an entirely different procedure for estimating the hot-spot. Based on Figs. 6 and 7 for oil and the chlorinated-diphenyl coolant, the procedure is to add to the top fluid temperature the gradient appropriate to that temperature, the duct size and the per-unit-

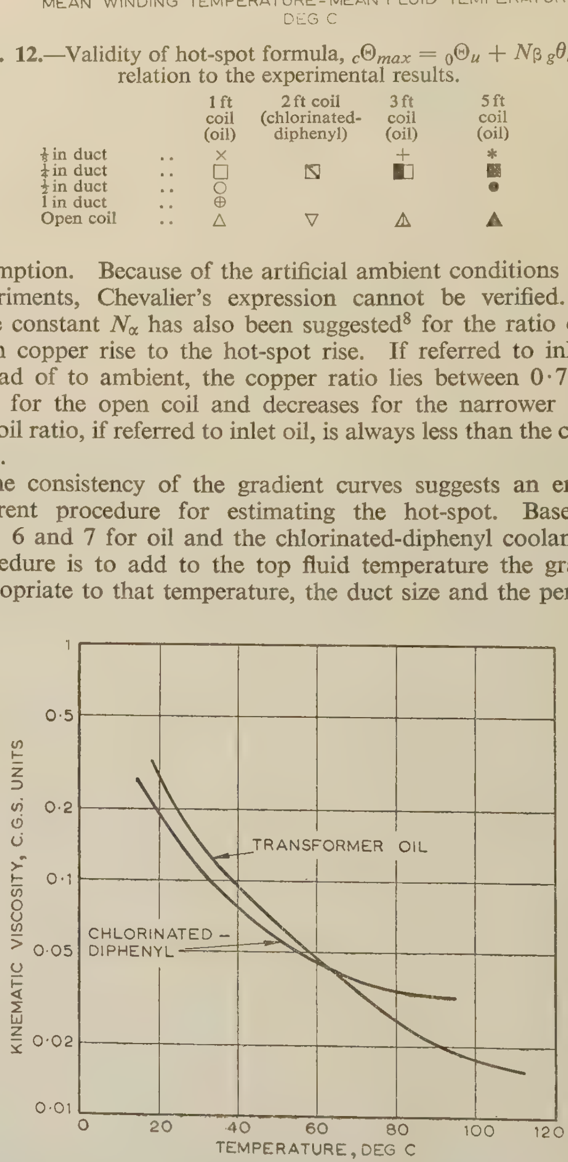

Fig. 13.—Variation of kinematic viscosity with temperature for transformer oil and a chlorinated diphenyl.

area dissipation at the top of the winding. The experiments show that for the 2 ft, 3 ft and 5 ft coils the ratio between the dissipation at the hot-spot temperature and the mean dissipation is approximately 1·07 for the $\frac{1}{8}$ in duct, 1·05 for the $\frac{1}{4}$ in duct and 1·03 for the open coil, for mean dissipations less than 1 watt/in^2. To calculate the hot-spot temperature of a transformer in service, therefore, it is not necessary to measure the mean copper temperature or estimate the mean oil temperature. The information required is the top oil temperature and, say, the primary current. From the design data of the transformer (exposed area of each layer) and the test results of the heat run carried out at the manufacturer's works (relation between current and copper loss), the average dissipation is readily calculated.

A similar method of calculation is proposed for disc-coil windings. Here the average copper temperature of the highest-but-one coil in the stack is calculated from Fig. 11 and the hot-spot temperature then estimated from the empirical data of the copper gradients within the disc coil.

(7) CONCLUSIONS

The following temperature relationships apply to layer-type and disc-type windings operating under steady conditions.

For a layer-type winding, within any single oil duct, the top and bottom oil temperatures will be fixed mainly by conditions external to it, in particular by the pattern of heat transfer from tank to surroundings. The shape of the oil-temperature distribution curve will be determined by the size of the duct.

Superimposed on the oil-temperature distribution the copper temperatures of vertical layer-type coils will take up local temperatures determined by an appropriate local convection coefficient, or, more empirically and usefully, by a temperature gradient associated primarily with a given power dissipation and oil temperature. These gradients depend only to a secondary degree on the duct size.

It can be inferred that the mean coil temperature distribution of a stack of horizontal disc coils forming a limb of a winding will be determined in a similar manner, except that end effects will be more marked because of the horizontal surfaces at the top and bottom coils. The convection coefficients are governed by a more complex relationship best defined by a correlation curve from which they can be calculated. The gradients within disc coils are most complex because of the large number of variables involved, but certain approximate rules may be made.

The heat-transfer data for layer windings can be treated by normal correlation methods. While this is of some interest in heat transfer, it appears to have little value for practical transformer design purposes. However, the correlation of the disc-coil results is essential in order to form a general conclusion. Whether this correlation applies to fluids other than oil, only further experiments can decide.

(8) ACKNOWLEDGMENTS

The authors wish to thank Mr. E. C. Rippon, Chief Transformer Engineer, for sponsoring this work and for his continued interest in it, and their colleagues in the Electrical Research Department for their practical assistance. The paper is published by permission of the Directors of C. A. Parsons and Co. Ltd.

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(10) APPENDIX: APPRAISAL OF PUBLISHED INFORMATION

Reference 1 contains a wide bibliography which deals mainly with the physics of convection but does not differentiate between its references as to immediate relevance.

Nolen[5] analyses data from a 150 kVA layer-wound transformer of 15 in. coil height having thermocouples in the oil and having the winding subdivided to allow detailed measurements of temperature by resistance, and concludes that distributions are closely parabolic. Demoulin and Marique[9] also discuss temperature distribution but the data lack detailed precision.

The index in eqn. (2) is established by general acceptance, and evidence for it taken on transformer coils is given by Nolen,[5] Vogel and Narbutovskih[11] and Montsinger.[3] This work is also evidence for the relevance of the correlation line established by general convection experiments to the relationship between temperature rise and coolant conditions in transformers.

On the physics of the convection process, Touloukian, Hawkins and Jakob,[12] Jakob and Dow[13] and Carne,[14] are in agreement that there is similarity between cylindrical surfaces of greater than 4 in diameter and plane surfaces; it follows that the effect of radius of curvature of transformer coils may be neglected in the heat-transfer mechanism. On the effect of coil height, Saunders[15] supplies some of the rare data, while Touloukian, Hawkins and Jakob correlated results for different heights in different liquids. Work by Gotter[16] on various sizes of zigzag heating elements with thin interturn insulation in transformer oil is of interest in that he recognizes the significance of the external tank conditions and also notes the discontinuity of the temperature distributions. The latter is also described by Griffiths and Davis,[17] Saunders,[15] Kennard[18] and Eckert and Soehnghen.[19]

There is an almost complete lack of information on horizontal ducts situated as in a transformer. A theoretical analysis by Steckler[20, 21] gives an interesting concept of the mechanism.

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THE PRINCIPAL CHARACTERISTICS AND GENERAL ANALYSIS OF A NEW EPICYCLIC DRIVE FOR ELECTRIC LOCOMOTIVES

By H. E. J. SYMES, M.Sc.(Eng.), Associate Member.

(*The paper was first received* 6*th May, and in revised form* 20*th December*, 1957.)

SUMMARY

In an effort to improve operating and technical characteristics and to eliminate some of the difficulties experienced when semi-skilled or unskilled persons are employed as drivers of electric locomotives in South African mines, an investigation was made to develop an improved, simple drive system having as many foolproof features as possible.

A drive consisting of two compound-wound d.c. motors coupled differentially to the road wheels through an epicyclic-gear unit was examined and found to meet the requirements. Subsequent tests on a 4½-ton experimental locomotive confirmed the features expected, and demonstrated in addition numerous useful characteristics not previously available on small locomotives.

Ease and sensitivity of control, electric braking at any speed, exceptional manoeuvrability, inherent limitation of both tractive and braking efforts to prevent wheel-slip and skidding, virtual elimination of sparking at the controller contacts, limitation of motor loading and line current for any combination of controller position, drawbar load and speed, inherent automatic acceleration and maximum power economy at any speed and load are some of the more attractive features.

The paper describes the drive and explains its basic characteristics by mathematical analysis.

LIST OF SYMBOLS

(Units are not specified, for the reasons given in Section 3)

I_L = Locomotive line current.
I_1, I_2 = Armature currents of No. 1 and No. 2 machines.
I_S = Stalled circulating current between machines.
I_F = Total shunt field current.
I_{F1}, I_{F2} = Shunt field currents of machines.
K, K_1, K_2, etc. = Conversion constants.
N = Output speed of the drive.
N_1, N_2 = Speeds of machines.
N_G = Machine speed (general).
N_S = Common speed of machines at locomotive stalling point.
P_1, P_2 = Power of machines.
P_L = Output power of locomotive.
P_S = Circulating power at locomotive stalling point.
R_C, R_B = Compensating or ballast resistance of controller.
R_F = Forward diverter resistance of controller.
R_R = Reverse diverter resistance of controller.
R_M = Minimum diverter resistance.
R_S = Resistance of shunt-field winding of one machine.
S_1, S_2 = Shunt excitation of machines.
T_1, T_2 = Torques of machines.
T = Output torque or tractive effort.
t = Series excitation factor of a machine (symmetrical compounding).
V = System voltage.
W = Locomotive weight.
Φ = General symbol for machine flux.
Φ_1, Φ_2 = Total or resultant fluxes of machines.

(1) INTRODUCTION

It is well known that there are several practical problems associated with the operation of small d.c. electric mining locomotives which have not been satisfactorily overcome. A review of the improvements to conventional machines since their introduction shows that they are of a minor nature only; little has been achieved in rectifying some of the more fundamental weaknesses familiar to users. In South African gold mines, the difficulties encountered are accentuated by the extensive employment of native drivers, most of whom, though capable and conscientious, can be classed as unskilled as regards their ability to handle equipment to the best advantage.

The shortcomings of conventional mining locomotives have recently been emphasized in the technical Press by a number of writers. Since the comments published in general supported the author's own experience, an investigation was instituted with the object of examining critically the fundamental principles of operation in order to solve as many as possible of the known problems.

While it was intended to retain the established good features of the conventional locomotive, the following improvements were sought:

(*a*) Improvement in the braking characteristic in the interest of safety, and a substantial reduction or elimination of locomotive brake-shoe wear, such wear having been found excessive where unbraked rolling stock is used and the locomotive duty includes loading and tipping cars individually.

(*b*) Elimination of controller-contact burning, without additional complications, to save maintenance time and cost.

(*c*) Simplification of manual control and the introduction of inherent foolproof features suitable for unskilled labour, such as the restriction within the limit of adhesion of maximum accelerating and braking efforts and the limitation of maximum motor loading.

(*d*) Modification to the system of control to improve accuracy and speed in manoeuvring, to reduce buffing shocks and to allow widely varying loads to be hauled easily and economically at any speed, i.e. to permit continuous control without overheating the resistors.

(*e*) Layout of equipment to facilitate better underground maintenance.

(*f*) Improvement in safety by minimizing the possibility of runaway conditions developing either by overspeeding or because of skidding while braking.

(*g*) Incorporation of safeguards for conditions when the locomotive is on special duty such as re-railing cars or other locomotives.

The investigation was combined with a similar analysis of various forms of drive for another purpose, and was accelerated

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Mr. Symes is a partner in the firm of Adams, Symes and Partners, Johannesburg.

by the fact that one of the drives appeared to provide a solution to many of the requirements. This system was eventually tested in an experimental 24 in-gauge trolley locomotive of 4½ tons weight. It was constructed from components procurable at the time and has been regarded essentially as a laboratory on wheels and not as a service locomotive. In many respects its performance on test exceeded expectations and provided sufficient data for the design and production of a prototype.

A description of the system with its characteristics follows. A mathematical and graphical analysis of the basic performance is included because, apart from its practical and academic interest, it gives the reader a better understanding of the features peculiar to the system.

(2) DESCRIPTION OF DRIVE

(2.1) Principle of Operation

The system consists essentially of two d.c. motors coupled respectively to two elements of a mechanically symmetrical epicyclic differential-gear unit, the third element of which is connected to the driving wheels of the locomotive. Fig. 1 in

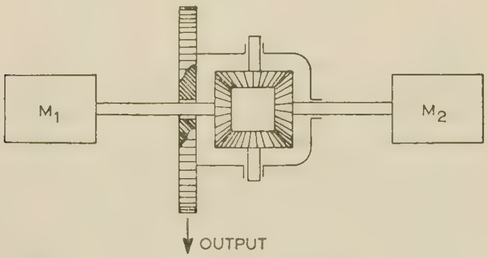

Fig. 1.—Diagrammatic representation of drive.

which M_1 and M_2 represent the two motors, shows the mechanical arrangement of the drive. For convenience the common bevel differential has been shown but other forms could be used equally well.

Once started, the two motors run continuously for the duration of operation of the locomotive, in a direction such that the drive output is stationary when their speeds are equal. If no torque is developed for this condition the motors may be regarded as idling. Movement of the locomotive is then caused by a change in speed of either motor, the direction of travel depending on which of the pair runs the faster. The motors themselves are not reversed or stopped at any time.

The armature circuits are permanently connected in parallel

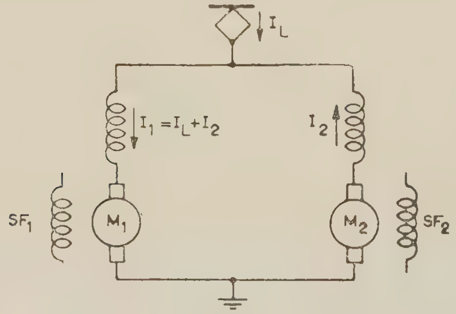

Fig. 2.—Principal armature circuit.

across the supply, as shown in Fig. 2. Series motors cannot be used because the idling speed on full voltage would be excessive. It is essential that the motors be shunt- or compound-wound. Variation in their speeds can then be accomplished by simple shunt-field regulation.

If a restraining load is applied to the output of the differential unit while the shunt fields are adjusted to develop tractive torque, it is found that the machines operate through the planetary wheels as a motor-generator in which the one with the weaker field is the motor (see Section 8.1).

The electrical output of the generator is returned to the motor through the closed armature loop (Fig. 2). Neglecting the motor and gear losses, therefore, the power taken from the system is the power actually developed at the locomotive wheels for any working load and controller speed. The drive is thus always economical in the accepted sense.

The starting condition is noteworthy. The shunt fields may be set for full tractive effort at the wheels without moving the load. The armature speeds are then equal, the locomotive output is zero, and the current taken from the system is that required for the losses only. The load is started from rest by a very small line current. The conditions of the well-known back-to-back test are thus reproduced at the commencement of acceleration. Once the load has been set in motion the motor-generator condition continues, but the motor then runs faster than the generator.

(2.2) Series Winding

The most interesting and useful features of the drive are introduced by the inclusion of series field windings as shown in Fig. 2. The polarity of the fields is such that the shunt excitation of a motoring machine is boosted by its series excitation. Under normal tractive conditions with fixed shunt-field settings the speed of the motoring or faster machine is thus reduced by the combined line and circulating currents in its series windings, while the speed of the generator is simultaneously increased by the demagnetizing circulating current in opposition to its shunt field. There is thus a reduction in the difference between the armature speeds or in the locomotive output speed, the magnitude of the reduction being dependent on the load. If the load is increased progressively there is an ultimate value at which the armature speeds are equalized and the locomotive is stalled, even though the shunt-field controller may be at its maximum setting. An important feature of the stalled condition is that the machines are left running and their self-ventilation continues. The maximum load it is possible to demand from them is clearly defined and always remains within the intended limit.

Current in the series windings thus cancels the difference in the shunt-field excitation of the two machines as set on the controller. The magnitude of the stalling tractive effort therefore depends on the position of the controller between its idling and maximum values as well as on the number of series turns. Starting from rest can be regarded as an instantaneous stalled condition.

It is therefore possible in the design of a locomotive to ensure that, for a given value of wheel-to-rail adhesion and a maximum controller setting, tractive wheel-slip does not occur, by arranging the drive to stall before slip starts.

If the static load is insufficient to stall the drive, acceleration takes place. The locomotive may be started from rest by setting the controller to full speed in a single quick step, the initial acceleration then being the maximum within the limit of wheel-slip. The line power simultaneously rises from the small stalling loss to the running value. When acceleration is by the conventional step-by-step method, the transitions are almost completely smoothed by the series windings.

The possibility of using cross-compounding between the machines to produce the same effect with a slightly improved

speed/tractive-effort curve has been considered, but rejected because there would be a tendency to instability under certain transient conditions.

It may be noted that the number of series turns need not necessarily be the same on both machines. If they are unequal the performance will be different for each direction of travel. Although this feature may be useful for certain applications it would not generally be suitable for a locomotive and would complicate starting-up from rest.

(2.3) Braking

It will be seen that if the output torque is reversed while its direction of rotation is unchanged the torque of each machine is also reversed. The functions of the machines are thus changed from motoring to generating and vice versa, so that the slower machine becomes the motor while the faster generates. It follows from the equal-torque relationship (Section 8.1) that the power output of the generator is greater than that of the motor, so that there is a net return of power to the system. Any braking operation by the drive involving a reversal of torque is thus regenerative and can be initiated, for example, by a controller movement towards the equalization of the shunt fields. A feature of the greatest importance is that regeneration is possible down to zero track-speed because the machines are always running fast enough to operate on the system voltage.

During braking the reversed currents in the series windings allow an increase in the speed of the faster generating machine and simultaneously reduce the speed of the slower. There is thus a gain in braking effort with higher locomotive speed, i.e. the speed/braking-effort characteristic for constant shunt fields is a rising curve, and braking is therefore quite stable in its application.[12]

Regenerative braking relies for its operation on the supply system being capable of absorbing the returned power. However, tests on the experimental locomotive operating on a rectifier system have proved that full braking is possible by current circulation around the closed armature and shunt-field circuits, but then all braking power is dissipated within the machines. It is known from tests that in a typical design the thermal capacity of the machines is sufficient to cater for all normal braking requirements.

(2.4) Control Circuit

A diagram of the control circuit is shown in Fig. 3. The shunt field windings of the two machines are permanently connected in

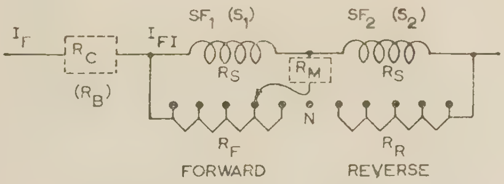

Fig. 3.—Shunt-field circuit.

series to ensure that creepage does not occur when the controller is at its neutral point and the temperatures of the two field windings are unequal. This is a condition which can readily appear after a long run in one direction.

R_F and R_R are the forward and reverse control resistances connected as diverters across the two shunt fields. The equipment can be simplified by using a single control resistance with suitable switching arrangements in the controller.

The resistance R_M is optional and is included only if the maximum tractive speed is to be definitely limited. As is shown later, the maximum power available from the drive is greater when R_M is omitted so as to allow a controlled shunt field to be completely short-circuited. The maximum speed of the locomotive in that case is theoretically unlimited.

It will be seen that the partial or total short-circuiting of either shunt field causes a rise in voltage across the field winding of the uncontrolled machine so that both fields are, in fact, subject to simultaneous control in the opposite sense. The shunt field of one machine may thus be subjected to half the system voltage when idling or to the total line voltage when functioning as generator at full tractive speed on the controller. The shunt field winding should thus be rated for a value between these limits, a higher value being adopted where trips are long.

Another control system tested on the experimental locomotive is that incorporating a variable compensating resistance R_C, mechanically coupled to the controller and arranged to maintain the overall shunt-field circuit resistance at a constant value. Steady maximum shunt excitation then occurs during idling and on the slower machine at any track speed. Such a system is obviously more complicated and more costly, and its advantages are insufficient to recommend its general adoption.

A useful compromise is that in which R_C (Fig. 3) is a fixed resistance to limit the range of variation in the shunt field of the uncontrolled machine. This serves also as a means of adjusting the relative values of the maximum desired tractive and braking efforts in a design.

The three systems give different performance characteristics in the locomotive and their comparison, in Section 3.3.1, is of practical as well as academic interest.

Connecting the two shunt fields in series, with individual diverter control, has the following further advantages:

(*a*) Only a fraction of the shunt field current is passed through the controller itself, so that it can be light and simple and have a relatively large number of steps. The diverter resistors need have only a small thermal rating and are therefore cheap and small.

(*b*) Conditions are not conducive to inductive arcing in the controller in either direction of movement, and long contact life may be expected without the necessity for arc-quenching devices.

(*c*) Since the controller itself is not in series with the main shunt-field circuit, controller faults cannot open the field circuit, which remains permanently connected across the supply. Furthermore, an open-circuit or bad contact in the controller automatically applies electric braking by equalizing the shunt excitation of the two machines.

The diverter resistances may be graded as desired. There is no necessity to conform to any system of mathematical progression between steps; two closely-graded inching steps on either side of the neutral position have been found useful on the experimental locomotive.

(3) ANALYSIS OF THE DRIVE

The basic characteristic features of the drive are probably best explained or understood by means of a mathematical and graphical examination of the performance of the two machines separately and in combination.

The mechanical properties of the differential gear are considered in Section 8.1.

For the purpose of purely qualitative analysis the expressions have been simplified by omitting the dimensions or units of the parameters.

Except where specially mentioned, the effect of internal losses is disregarded, since their inclusion would not only complicate the analysis unnecessarily but would tend to obscure some of the more important basic features it is desired to emphasize. Steady-state conditions, or transients during acceleration and

retardation sufficiently slow to be regarded as steady, are assumed for the determination of the more important characteristics.

It should be noted that torque and tractive or braking effort are generally regarded as synonymous for the purpose of the analysis.

(3.1) The Assumption of a Linear Magnetization Curve

The analysis can be carried out by a purely graphical method assuming a typical or known magnetization curve for the machines, or the problem can be considerably simplified and treated mathematically by considering the magnetization curve as a straight line. When using the latter method some accuracy is sacrificed but the resultant error is not nearly so great as may be expected. This is because the drive characteristic depends mainly on the behaviour of the faster machine, which, having weak shunt excitation, operates mostly on the unsaturated portion of its magnetization curve. Actual analysis by both methods on a particular example has confirmed that the use of a linear magnetic characteristic is justified, particularly for an initial determination of the more important quantities in a design or for studying the behaviour of the drive. If necessary, a final check can always be made by the graphical method.

The error in the characteristic of a machine, to the extent that the drive is affected, i.e. the variation in its speed for a given deviation or error in its excitation, can be simply demonstrated as follows:

$$N_G = \frac{K}{\Phi} \text{ or } \frac{dN_G}{d\Phi} = -\frac{K}{\Phi^2}$$

For large or saturation values of Φ (i.e. flux in the slower machine) the error in N_G is comparatively small. When Φ is small (i.e. in the faster machine) the actual curve and assumed line are nearly coincident, so that the error is again small [see Fig. 4, curve (*a*)].

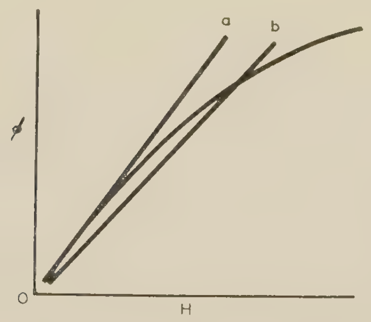

Fig. 4.—Straight-line approximation to magnetization curve.

The greatest error can be further reduced by placing the assumed magnetization line relative to the true curve as shown at *b* in Fig. 4.

On these assumptions it is permissible to regard the ampere-turns in the field coils and the field strength (or flux) as synonymous quantities, while series and shunt field strengths may be added or subtracted arithmetically to obtain the resultant excitation of a machine.

(3.2) Torque/Speed Curves

Since its total flux can be written $(S_1 + I_1 t)$, the speed of the faster machine M_1 can be expressed by

$$N_1 = \frac{1}{\Phi_1} = \frac{1}{(S_1 + I_1 t)} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

At constant voltage the current is proportional to the power, which can also be expressed as the product of speed and torque, or $I_1 = T_1 N_1$. Substituting this value in the above expression, $N_1 = 1/(S_1 + T_1 N_1 t)$, from which

$$T_1 = \frac{1 - S_1 N_1}{t N_1^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

or

$$N_1 = \frac{-S_1 \pm \sqrt{(S_1^2 + 4T_1 t)}}{2T_1 t} \quad . \quad . \quad . \quad (3)$$

Similarly for the slower machine M_2,

$$T_2 = \frac{S_2 N_2 - 1}{t N_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

or

$$N_2 = \frac{S_2 \pm \sqrt{(S_2^2 - 4T_2 t)}}{2T_2 t} \quad . \quad . \quad . \quad . \quad (5)$$

If N_1 and N_2 are plotted against T_1 and T_2 the curves M_1 and M_2 of Fig. 5 are obtained. With reference to M_1, it is apparent

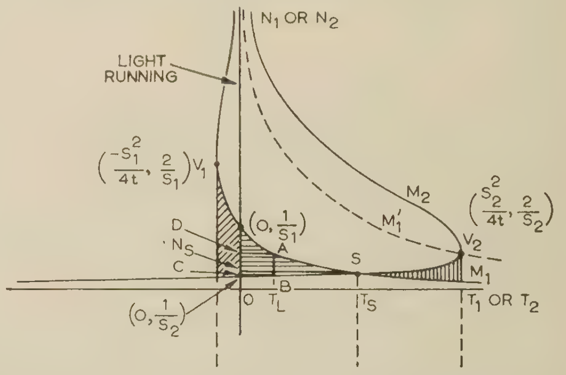

Fig. 5.—Machine speed/torque curves for $S_1 \neq S_2$.

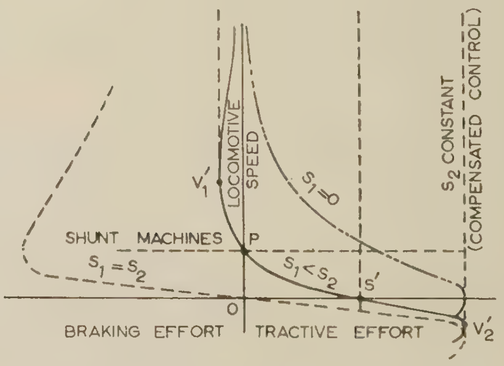

Fig. 6.—Locomotive speed/torque curves.

from eqn. (3) that there is a minimum value of the function when $S_1^2 + 4T_1 t = 0$ or $T_1 = -S_1^2/4t$. Also, from eqn. (3), the corresponding value of N_1 is $2/S_1$ giving point V_1. From eqn. (2), the intersection of the curve on the N axis occurs when $(1 - S_1 N_1) = 0$ or $N_1 = 1/S_1$.

Similarly, the curve M_2 has a maximum point V_2 at $T_2 = S_2^2/4t$ and $N_2 = 2/S_2$, the intersection on the N axis occurring at $1/S_2$.

The stalling point, where both speeds and torques are equal, is at S, the corresponding maximum tractive effort being proportional to T_S and the common speed N_S.

These curves also demonstrate that the maximum possible tractive effort of the locomotive is limited by the characteristic

of the slower machine, while the maximum regenerative braking torque is determined by that of the faster.

(3.2.1) The Condition for $S_1 = 0$.

When S_1 is short-circuited, eqn. (2) becomes $T_1 = 1/tN_1^2$. If this is plotted, the dotted curve M_1', which does not intersect the axes, is obtained. It can be demonstrated that the M_1' curve crosses the M_2 curve at the point of maximum torque of M_2 as follows: At the point V_2 of maximum torque the speed of M_2 is $2/S_2$. When M_1 runs at this speed its torque is given by

$$T_1 = 1/tN_1^2 = 1/t \times S_2^2/4 = S_2^2/4t$$

the maximum torque of M_2.

It is thus seen that when S_1 is zero the locus of all points indicating the maximum tractive effort of the locomotive when S_2 is varied is the curve M_1'.

(3.2.2) Locomotive Speed.

Since the torques of the two machines are always equal, it follows that any vertical intercept between the curves is a measure of the locomotive speed. Thus AB is its speed when its tractive effort is T_L. This condition applies to any intercept in the horizontally shaded area. In the diagonally shaded portion T_L is negative, resulting in regenerative braking of a maximum possible effort of $-S_1^2/4t$ while the vertical intercept still gives the locomotive speed. The vertically shaded area is for the condition where the locomotive is forced backwards against the forward setting of the controller.

(3.2.3) Locomotive-Speed/Tractive-Effort Curve.

To the user, the speed/tractive-effort curves of the locomotive are the most important. These can be derived from Fig. 5 by plotting the locomotive speed, or the length AB, against the corresponding tractive effort, or T_L. The result is shown in Fig. 6 in which, for convenience, tractive-effort values are projected from Fig. 5, bearing in mind the scale factor of 2 to allow for the addition of the equal machine torques. The full curve is for the same values of S_1 and S_2 as used in Fig. 5 while the dotted curve is obtained when the controller is at neutral, i.e. when $S_1 = S_2$.

The curve PS′ is the normal tractive characteristic for a particular position of the controller, S′ being the stalling point, while P gives the speed unloaded. Between P and V_1' braking occurs. As expected, the dotted curve lies wholly in the braking zone and passes through the idling point at the origin when the locomotive is stationary.

The chain-dotted curve is obtained when $S_1 = 0$, i.e. the shunt coil short-circuited, and corresponds to curve M_1' in Fig. 5. Comparing this curve with the full one it is noted that the tractive effort at the stalling point is considerably greater, but the maximum tractive speed is no longer limited, regenerative braking being impossible for this condition. A very important feature of this curve is its vertical trend in the vicinity of the stalling point. It means that the tractive effort developed during an automatic start remains almost constant at the maximum value until the greater part of the rated speed is reached, resulting in a close approximation to the ideal acceleration.

(3.2.4) Output Power.

In Fig. 5 the locomotive running power is given by the length AB multiplied by the tractive effort T_L, i.e. by the area of the rectangle ABCD.

(3.2.5) Idling and Emergency Braking.

If the curves in Fig. 5 are plotted when $S_1 = S_2$ they take the symmetrical form shown in Fig. 7. No tractive power area is

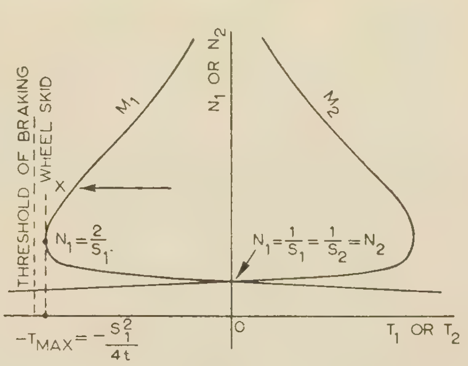

Fig. 7.—Machine speed/torque curves for $S_1 = S_2$.

enclosed, only braking being possible. The curves thus represent the stationary idling and emergency braking conditions when the controller is suddenly returned to neutral either manually or through a dead-man's handle.

It is important to note that the maximum braking torque of M_1 occurs when its speed is $2/S_1$, while its speed at the idling point is $1/S_1$, i.e. the maximum braking effort occurs when the speed of the faster machine is twice its idling speed. Consequently, if a range of control is used in which the shunt-field variation is more than 2 : 1 while the shunt field of the undiverted machine remains constant, initial braking can occur at a point such as X beyond or less than the maximum. This fact is advantageous or not, depending on the circumstances. It is known that an algebraically positive slope on a braking characteristic curve such as at X can be regarded as unstable.[12] In this instance, instability resulting in a runaway condition can only occur if the braking force X is insufficient to reduce the train speed, as, for example, on a steep grade. Such instability is rarely obtained in practice because the necessary machine speed is excessively high before there is any appreciable diminution in braking effort, while the accompanying increased losses tend to restore some of the lost braking torque. Instability of this nature would rather indicate unsafe overloading of the locomotive as regards its braking duty.

On the other hand, an advantage of this feature is its cushioning effect if full braking is applied suddenly at high speed, incipient wheel skidding being unlikely at the low initial braking effort; the braking increases to its maximum as the speed falls. The condition can be avoided entirely by the use of a system of control in which the idling speed of a machine is at least half its maximum permissible speed.

As a guide to the diminution of braking force to be expected at very high speed, consider the example of a pair of machines having a speed range of 4 : 1 with shunt-field control and constant maximum shunt-field on the slower one. Assume sudden maximum braking force to be applied from full speed at no load. The value of N_1 at X is then $4/S_1$, $1/S_1$ being the idling speed. Then $T_1 = (1 - S_1N_1)/tN_1^2 = -3S_1^2/16t$. Since the maximum possible braking torque is $-S_1^2/4t$ the ratio of reduced torque to maximum torque is 3 : 4, or 25% reduction, neglecting losses.

(3.3) Current and Power Circle Diagrams

Of the performance curves, the circle diagram is probably the most useful and informative.

Since $T_1 = I_1\Phi_1 = (I_1S_1 + I_1^2t) = T_2 = I_2\Phi_2 = (I_2S_2 - I_2^2t)$, it follows that

$$I_1^2 + I_2^2 + \frac{S_1I_1}{t} - \frac{S_2I_2}{t} = 0 \quad . \quad . \quad . \quad . \quad (6)$$

If this is plotted with I_1 and I_2 as axes, it is a circle with centre at $I_1 = -S_1/2t$ and $I_2 = S_2/2t$ and of radius $\sqrt{(S_1^2 + S_2^2)}/2t$. It also passes through the origin and may be called the *current circle diagram* (see Section 8.2).

Another form is the *power circle diagram*, in which the currents I_1 and I_2 are replaced by P_1/V and P_2/V, where P_1 and P_2 are the power of the machines M_1 and M_2 respectively, and V is the system voltage, normally regarded as constant.

Eqn. (6) may be rewritten and transformed to

$$P_1^2 + P_2^2 + \frac{VS_1P_1}{t} - \frac{VS_2P_2}{t} = 0 \quad . \quad . \quad . \quad (7)$$

But the values of shunt excitation S_1 and S_2 are themselves proportional to the system voltage and can be rewritten VS_1 and VS_2, where S_1 and S_2 are the shunt excitations at a specified nominal voltage of, say, unity. Eqn. (7) then becomes

$$P_1^2 + P_2^2 + \frac{V^2S_1P_1}{t} - \frac{V^2S_2P_2}{t} = 0 \quad . \quad . \quad . \quad (8)$$

When this circle is plotted on a co-ordinate system with P_1 and P_2 as axes the circle has its centre at $P_1 = -V^2S_1/2t$ and $P_2 = V^2S_2/2t$, and the radius is $V^2\sqrt{(S_1^2 + S_2^2)}/2t$.

Generally the power circle is more useful than the current circle because the effect of voltage variation can also be studied; it is plotted in Fig. 8. Since the co-ordinates of the centre of

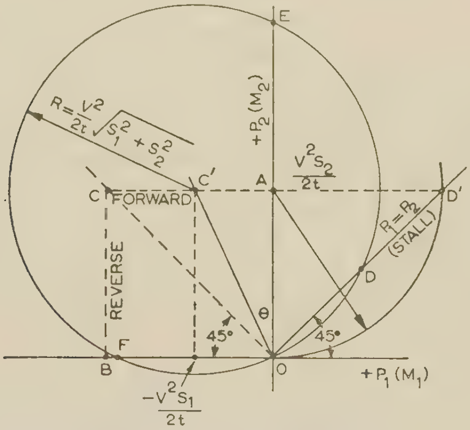

Fig. 8.—Power circle diagram.

the circle contain S_1 and S_2 it follows that there is separate circle passing through the origin for every position of the controller, assuming the voltage to remain constant. In the particular instance when S_1 represents the short-circuited field coil the centre lies on the axis of P_2.

(3.3.1) Locus of Circle Centres.

The position of the centre of the circle will be shown to be of great importance in determining the performance of the locomotive. As already seen, the co-ordinates of the centre as determined by S_1 and S_2 depend both on the position of the controller and on the system of control used. For each system of control there is a definite locus of circle centres for variation in controller position.

The three basic arrangements indicated in Section 2.4 are examined as follows:

(*a*) S_2 maintained constant while S_1 is varied, i.e. a compensated system (Fig. 3 with R_C in circuit).

(*b*) S_1 and S_2 varied simultaneously (Fig. 3 with R_C omitted).

(*c*) As for (*a*) but having a fixed ballast resistance R_B inserted in place of R_C.

(*a*) Since S_2 is constant while S_1 is varied, it follows that the centre locus is the horizontal line $P_2 = V^2S_2/2t$, its end points being $-V^2S_1/2t = 0$ for the full-speed condition when S_1 is for the short-circuited coil, and $-V^2S_1/2t = V^2S_2/2t$ when idling. The centre of the idling circle is thus always on the 45° line OC for $P_2 = -P_1$, where also $S_1 = S_2$ numerically. The line CA is then the required locus for forward travel. Similarly, CB is the lucus for reverse motion of the locomotive, the point B being the full-speed position when S_2 is for the short-circuited coil.

Since there is no compensating resistance in circuit in the idling position, the lengths CA and CB are respectively proportional to the voltages across SF_1 and SF_2, or CA + CB represents the system voltage. On one of the running notches having centre C′ the voltage across SF_2 is still CB, while C′A is the voltage across SF_1. CC′ is thus the voltage drop in the compensator.

(*b*) In Fig. 3, I_F is the total shunt-field current, I_{F1} is the current through SF_1 and R_S is the undiverted resistance of each shunt field, SF_1 being the shunt field winding of the controlled machine.

Then $V = I_FR_S + I_{F1}R_S$ or $I_F = V/R_S - I_{F1}$. Since the strength of S_1 and S_2 are respectively proportional to I_{F1} and I_F it is permissible to write $S_2 = V/R_S - S_1$ and, multiplying by $V^2/2t$, the equation becomes

$$\frac{V^2S_2}{2t} = \frac{V^3}{2tR_S} - \frac{V^2S_1}{2t} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

This expression is dimensionally the same as the quantities associated with shunt field on the circle diagram, and gives the relationship between S_1 and S_2 for this form of control. When plotted on the P_1 and P_2 co-ordinate system it is seen to be a straight line with a slope of 45°, the coefficients of S_1 and S_2 being numerically equal, S_1 being measured to the left of the origin, and S_2 upwards. Also, it has already been seen that $V^2S_2/2t$ and $-V^2S_1/2t$ are the co-ordinates of the circle centre, so that this straight line is in fact the required locus and is the line AB in Fig. 9, the end points being A and B. OC is again

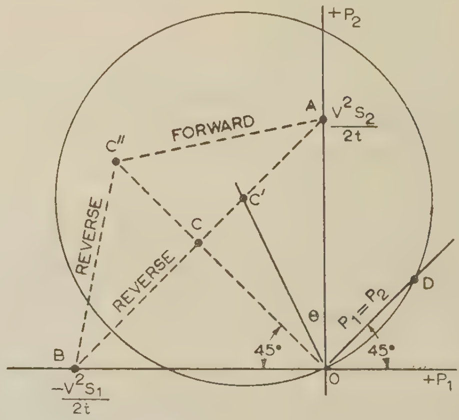

Fig. 9.—Effect of control system on position of circle centre.

the idling line, so that CA is the section for forward control while CB is for reverse travel. If the values of shunt field at A and B are made the same for both Figs. 8 and 9, it is seen that the circle diameters at full speed are the same for either system of control; but for intermediate positions on the controller, such as at C′, the present arrangement results in generally smaller circles. In Figs. 8 and 9 the angle θ subtended by the circle centre at the origin has been made the same in both diagrams so that the ratio of the shunt fields is unchanged and

$\theta = \arc\tan S_1/S_2$. It should be noted that the idling speed at C in Fig. 9 is exactly twice that at C in Fig. 8 owing to the 2 : 1 ratio in the shunt fields for the two systems of control. The rating of the field coils should therefore be borne in mind when deciding on the system of control to be used. In Fig. 9 the generating machine is at maximum shunt excitation only when the controller is at full speed, the shunt excitation being at half strength for idling. Under the conditions of Fig. 8 a machine may operate at maximum shunt excitation for long periods both at full speed and when idling. Against this, the idling speed in the latter case is twice that of the former.

(*c*) It can be shown that, if a fixed ballast series resistance R_B is added in place of R_C in Fig. 3, eqn. (9) for the locus of the circle centre becomes

$$\frac{V^2S_2}{2t} = \frac{V^3}{2t(R_S + R_B)} - \frac{V^2S_1R_S}{2t(R_S + R_B)} \quad . \quad . \quad . \quad (10)$$

As before, this expression is linear where S_1 and S_2 are the variables, but the slope is now $R_S/(R_S + R_B)$ instead of unity. If the field-coil ratings and resistances are so fixed that the centres of the top-speed circles again coincide with A and B in Fig. 8 or Fig. 9, the locus for forward travel becomes AC″ in Fig. 9, its symmetrical counterpart for the reverse direction being BC″. System (*c*) is therefore a compromise between arrangements (*a*) and (*b*).

(3.3.2) Stalling Condition.

Since the drive runs as a simple motor-generator combination when stalled, the power associated with the motor is the same as that of the generator. Thus the 45° line OD on which $P_1 = P_2$ is the locus of stalling points (Figs. 8 and 9). In Fig. 8 a portion of the circle OD′ has been added for $S_1 = 0$. It is seen that the stalling point D' occurs when the machine M_1 develops its maximum power.

(3.3.3) Operating Range on Diagram.

At the origin 0, Fig. 8, the power of both machines is zero, irrespective of the values of S_1 and S_2. This is the light-running point for the conditions under consideration, or the idling point when $S_1 = S_2$. D (or D′) is the stalling point, so that the normal tractive operating range is the arc OD (or OD′). It is shown in Section 8.1 that $P_1/P_2 = N_1/N_2$. Thus any intersection on the P_1 or P_2 axes other than at the origin, represents infinite speed of the locomotive, since a machine speed can never be zero. E and F are two such points, E being reached from D if the locomotive is hauled backwards against a forward controller setting. The arc OF is the regenerative braking range, F representing complete runaway at high speed.

(3.3.4) Idling Circle.

It is noted that the stalling locus is tangential to the idling circle at its origin. An intersection for the stalling point is therefore impossible.

(3.3.5) Output Power.

In Fig. 10 the output power when operating at a point such as P is given by $P_1 - P_2$ or PX − PY or PZ + ZX − PY. But ZX = PY because Z lies on the line $P_1 = P_2$. Therefore output power is given by PZ or the intercept between the chord and the arc parallel to the axis of P_1. It may be noted that the intercept PZ′ parallel to the P_2 axis could also be used as PZ = PZ′.

For particular values of S_1 and S_2 it is obvious that the maximum locomotive power occurs when PZ has its greatest length at P′ on the tangent parallel to OD. Thus for P in Fig. 10, the length OQ is the locomotive power and QY is the generator power, the latter being the motor output less the locomotive output.

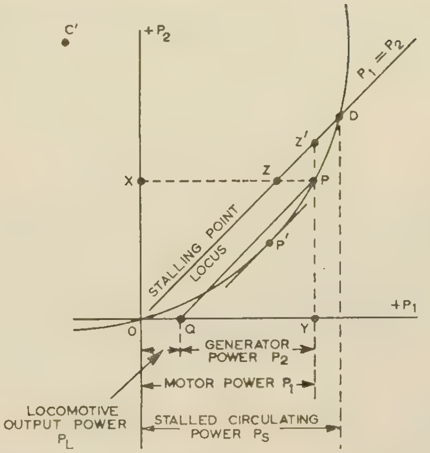

Fig. 10.—Circle diagram: segregation of machine and locomotive power ($S_1 \neq 0$).

The absolute maximum locomotive power occurs when $S_1 = 0$ and the centre of the circle lies on the P_2 axis. When the locomotive is stalled at $S_1 = 0$, P coincides with D, the output OQ is zero, and motor, generator and circulating power values are all equal.

(3.3.6) Locomotive and Machine Power Ratios ($S_1 = 0$).

Since it is normally suggested that the shunt-field winding of the controlled machine be short-circuited to obtain the maximum power from the combination, the powers associated with the individual machines at the principal operating points of the locomotive (maximum power and stalling) are examined for this condition only. Fig. 11, constructed in the manner of Fig. 10, enables this to be done.

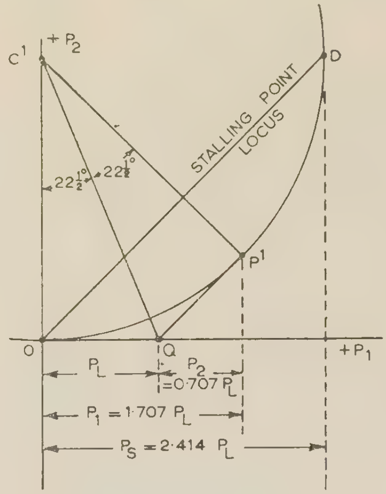

Fig. 11.—Circle diagram: machine and locomotive power relationships ($S_1 = 0$).

Then, for a specified maximum locomotive tractive power P_L, the corresponding power of the motor and generator, P_1 and P_2, at P′ can be found as follows:

Joining QC′, OQC′ and P′QC′ are identical triangles, from which

$$QP' = P_L \text{ and } P_2 = \frac{P_L}{\sqrt{2}} = 0{\cdot}707P_L \quad . \quad . \quad (11)$$

and

$$P_1 = P_L + P_2 = P_L\left(1 + \frac{1}{\sqrt{2}}\right) = 1{\cdot}707P_L \quad . \quad . \quad (12)$$

The maximum stalled circulating power P_S that the machines are required to develop is found from the fact that, P_S being equal to OC′, the circle radius,

$$P_L = P_S \tan (45/2)^\circ = P_S(1 - \cos 45^\circ)/\sin 45^\circ$$

and
$$P_S = \frac{P_L}{(\sqrt{2} - 1)} = 2{\cdot}414 P_L \quad . \quad . \quad . \quad (13)$$

Eqn. (13) is important because it represents the most arduous condition under which the drive can possibly operate, i.e. when stalled by the load or at the start of an automatic acceleration while the controller is at full speed. The whole of the circulating power must be carried through the epicyclic planetary wheels so that a determination of this quantity is of considerable impor-

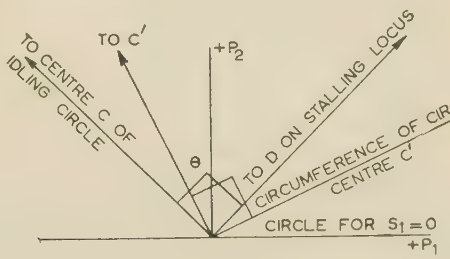

Fig. 12.—Circle diagram for simple shunt machines.

tance in the mechanical design. The expression also indicates the maximum load (or overload) to which a machine can be subjected. From a knowledge of the anticipated service conditions a suitable basic rating can be assessed for the machines.

Since the machine torques are equal, their speeds are proportional to their power, and the ratio of machine speeds for maximum locomotive power is $1{\cdot}707 : 0{\cdot}707$ or $2{\cdot}414 : 1$.

The significance of the type of control as regards performance characteristic should now be apparent. All power quantities are dependent on the size of the circle, which, in turn, is determined by the position of its centre.

(3.3.7) **Starting Current (Automatic Acceleration).**

The line power (or current at constant voltage) during the accelerating period of an automatic start to full speed is given with a fair degree of accuracy by the intercept PZ in Fig. 10, beginning at D and finishing at the steady operating point. The line current during the acceleration thus starts from zero and may or may not pass through the maximum value at P′, depending on the load. If the load is very heavy but insufficient to cause stalling, a balancing condition is reached between D and P′. For a light load, the operating point is between P′ and 0.

The important feature is that the starting current or power drawn from the line can never exceed the normal rated value P_L.

(4) PRACTICAL SIGNIFICANCE OF DRIVE CHARACTERISTICS

The principal operating characteristics and their derivation have been considered in some detail. A further explanation or summary of the features of the locomotive, with their significance and interpretation in actual service, will now be given.

Both from the experimental work done and from purely theoretical considerations the utility of the system as applied to, say, a mining locomotive may be considered under the following broad headings:

(*a*) Handling qualities.
(*b*) Direct technical advantages.
(*c*) Secondary advantages.
(*d*) Disadvantages.

(4.1) Handling Qualities

The ease with which the locomotive can be controlled is one of its most obvious features. As a demonstration, the experimental locomotive has been successfully driven by a four-year-old child, alone on the footplate. Both power and braking for forward and reverse travel are controlled through a single hand-wheel, which, being simply a shunt-field regulator, is much lighter to operate than a drum or camtactor-type controller with hand brake, and does not fatigue the driver. Also, his attention is not distracted from his train movement by the necessity of frequent changes of his grip from one control to another.

Control is inherently very smooth and can easily be made more so by the inclusion of additional steps in the field diverter. The jerk through the transmission normally experienced on the first controller notch of conventional locomotives is virtually absent.

The response of the locomotive to the controller for both power and braking is practically instantaneous, as is also the response to the release of braking effort.

The accuracy of control is very much greater than is possible on a conventional locomotive, so that manoeuvring or shunting operations can be carried out very rapidly and without delays or buffing shocks. Loose-coupled trains can be started and stopped smoothly, and fly-shunting is simple.

Acceleration makes no demands on the driver's skill and may be accomplished either in a single movement of the controller or by the usual step-by-step method.

Starting a train on a rising gradient presents no difficulties.

The drive is virtually foolproof as regards injudicious manipulation of the controller. On the experimental locomotive this has been demonstrated many times by moving the controller to full reverse in a single step while travelling forward at speed, this being regarded as the worst kind of abusive handling that could be devised. On no occasion while the locomotive was being retarded and brought up to speed in the opposite direction was the current large enough to trip the lightly-set line breaker. While such handling is obviously not recommended as normal procedure, the demonstration has served to indicate the controlling or limiting feature inherent in the drive. It is particularly suitable for unskilled personnel.

(4.2) Direct Technical Advantages

When the shunt field of the faster machine is not short-circuited there is a definite maximum speed which cannot be exceeded without electric braking occurring.

The maximum line current is known and clearly defined. This greatly facilitates the determination of circuit-breaker settings and, for trolley installations, assists in the design of overhead and substation equipment.

Every position of the controller is an economical running notch in the traction sense, in that no heavy-current series resistors are used.[8] The locomotive can run indefinitely with any load on any step of the controller. At creep speed, full load can be hauled on about one-quarter of the line current normally used by a comparable series locomotive.

It is impossible to overload the machines, since stalling occurs before this can happen, the load at the stalling point being suitably correlated with the rating.

For an assumed coefficient of adhesion between wheel and rail it is possible to design the drive so that wheel-slip does not occur during the maximum possible acceleration, while at the same time wheel-skid can be avoided during the greatest possible braking effort.

All braking down to standstill, both normal and emergency, is electric. There is no wear and tear on mechanical service

brakes and therefore no shoe dust liable to cause miscellaneous troubles.

Automatic acceleration, up to full speed or any intermediate speed, is an inherent feature.

Once the machines have been started, no heavy-current circuits are made or broken during the time the locomotive is in service. All control is effected on the shunt-field circuit; the diverter system used is not conducive to arcing and fails to safety in the event of an open-circuit in the controller.

The performance characteristic can easily be varied over a wide range either in the design or on a completed locomotive.

Since any load is started from rest at a line current equal to the losses only, it follows that for a trolley system there is practically no voltage loss in transmission during starting and initial acceleration.

The limitation of peak running currents, the small starting current and the availability of regeneration for all braking indicate that the system could be applied with advantage to battery locomotives, provided that the machines were stopped during long idle periods.

(4.3) Secondary Advantages

The following features, while not particularly important, are of practical use.

A train can be held stationary on an incline merely by setting a holding torque on the controller, thus providing in effect an anti-run-back feature.

Very little heat is dissipated from resistors—a good feature in deep, poorly ventilated mines and an advantage where flame-proof equipment is required.

The ventilation of the machines is good and their rating is high, since they run continuously irrespective of the locomotive speed. Also, because their rotation is unidirectional, efficient fan design is possible and separate blowers are unnecessary even on the largest locomotives.

For servicing and adjustment, the machines can be rotated by hand without the necessity of moving the locomotive. In addition, when isolated from the power supply, the locomotive can be hauled by another unit at a speed considerably greater than the normal full speed under its own power, without damage to the armatures, which, when their rotation is unimpeded, revolve at speeds additive with respect to the road wheels.

The locomotive is particularly suitable for special duties such as re-railing, since the control of torque is sensitive for both increasing and decreasing step-by-step values on the controller.

A section gap in the overhead line can be negotiated on load without returning the controller to neutral and without arcing. This results from the ability of the locomotive to maintain its own voltage for short periods. Similarly, no severe sparking occurs during momentary loss of contact at the collector.

The system can be arranged for the simultaneous control of two locomotives coupled together, using only light-current jumpers.

The drive is suitable for very narrow-gauge railways.

(4.4) Disadvantages of the System

In assessing the value of the drive the following disadvantages should be noted.

The full-speed efficiency is slightly lower than that of the conventional locomotive.

It is not possible to obtain an output power of more than about one-third of the total installed motor capacity, assuming the faster machine to run at its rated capacity when the locomotive power output is a maximum.

On very low voltages the circulating current for stalling may be very high with established designs of motor.

The design of the epicyclic gear must be good, and this item tends to be expensive.

(5) CONCLUSION

The results of the experimental work so far completed have been very encouraging and have clearly demonstrated the practical feasibility of the system. Its stability and simplicity, coupled with that all-important characteristic in mining locomotives, good braking, are most satisfactory. However, any attempt at this stage to apply the system indiscriminately would be inadvisable, because at present it would seem most suited to a restricted type of duty, such as shunting or the operation of a short shuttle service, as is normal on mine haulage systems. The exceptionally good track qualities, ability to stop and reverse rapidly, quick and accurate response to control, together with power economy at low speeds with heavy loads, are desirable features not found on conventional locomotives.

It has been suggested that the installed motor capacity could be used to better advantage if the machines were arranged to work additively as well as differentially. This is not a new idea and it has been rejected because of its complexity and also because so many of the desirable characteristics would be lost.

It is also obviously possible to incorporate a multitude of refinements to modify the characteristic in an effort to achieve the desired optimum, but it should be stressed that the drive has been developed in its present form in the interest of simplicity, reliability and safety. In its mining application, where easy handling and maintenance are important requirements, it is considered that the arrangement here described provides very good overall operating characteristics while omitting complicated equipment or circuits that may be a source of trouble in service.

(6) ACKNOWLEDGMENTS

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(8) APPENDICES

(8.1) Speeds and Torques in the Differential Gear

A full analysis of the behaviour and characteristics of the epicyclic differential gear with regard to speeds and torques of the three elements for all the epicyclic inversions is given in Reference 7. However, Fig. 13 indicates briefly the more important aspects of the transmission which affect the two machines and the output.

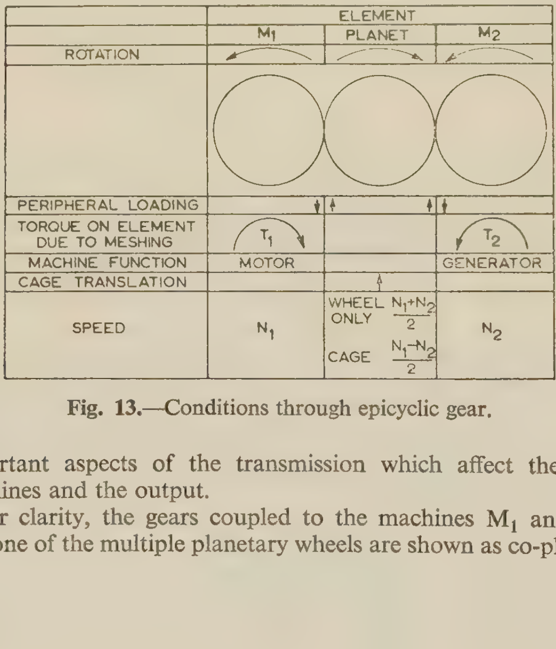

Fig. 13.—Conditions through epicyclic gear.

For clarity, the gears coupled to the machines M_1 and M_2 and one of the multiple planetary wheels are shown as co-planar. To ensure rotation of the planetary unit only without translation of its axis when the machine speeds are equal, i.e. for idling, the directions of rotation of M_1 and M_2 must be as shown. If the bodily movement of the planetary unit is restrained by the mechanical load on the drive while the speed of M_1 is increased by shunt field adjustment, it follows that the speed of M_2 must also be raised whilst its field is constant. The function of the latter machine is thus changed by the load from motoring to generating.

This feature is also apparent from an examination of the torque distribution. Reference to Fig. 13 indicates that, whereas the rotation and torque of the motor element M_1 are in opposite directions, those of M_2 are in the same direction, making M_2 a generator.

In any form of epicyclic differential unit which is mechanically symmetrical with respect to the two machines it is apparent that the two peripheral or tangential loads on the planetary wheel must be equal under steady conditions. It therefore follows that the torques on M_1 and M_2 are always of the same magnitude, or $T_1 = T_2$ numerically. Hence, the power associated with each machine is directly proportional to its speed.

It may be seen from the complete differential assembly (Fig. 1) that the machines rotate in opposite directions with respect to the differential while they function as motor and generator under load. The torques applied by both machines to the cage are therefore in the same direction or additive. This fact is also indicated in Fig. 13, where it is seen that the two peripheral loads on a plantetary unit at the ends of its meshing diameter are in the same direction. The driving reaction at the axis of the planetary wheel is thus the sum of these two loads.

The following relationship is then obtained:

$$T = T_1 + T_2 = 2T_1 = 2T_2$$

Since the torques are equal it follows that the power and current of each machine are proportional to its speed, i.e. $P_1/P_2 = N_1/N_2 = I_1/I_2$.

The motor-generator condition is present whenever the drive is loaded, irrespective of whether the locomotive is stationary or moving, or whether braking or tractive effort is developed at the road wheels.

For the speed relationships it is seen from Fig. 13 that the output speed of the cage is $(N_1 - N_2)/2$.

(8.2) Some Properties of the Circle (Section 3.3)

The general equation of a circle is

$$x^2 + y^2 + 2gx + 2fy + c = 0$$

Compared with the expression obtained in Section 3.3, this gives $g = V^2S_1/2t$ and $f = -V^2S_2/2t$. The radius is $\sqrt{(g^2 + f^2 - c)}$ which becomes $V^2\sqrt{(S_1^2 + S_2^2)}/2t$, since c is zero. In the absence of c the curve is constrained to pass through the origin.

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EDDY CURRENTS AND WALL LOSSES IN SCREENED-ROTOR INDUCTION MOTORS

By R. L. RUSSELL, M.Sc., Associate Member, and K. H. NORSWORTHY, B.Sc., Graduate.

(*The paper was first received 23rd September, and in revised form 6th November*, 1957.)

SUMMARY

The problem of circulating corrosive liquids assumes a major importance in nuclear-engineering practice, where the standards of safety and reliability which are imposed demand sealed circulating systems. One method employs a completely enclosed centrifugal pump driven by a squirrel-cage induction motor in which the rotor is separated from the stator by a thin cylindrical corrosion-resistant shell which is situated in the air-gap of the machine and effectively forms part of the retaining wall of the circulating system. A precise assessment for design or development purposes depends on a knowledge of the power losses in the stationary shell and it is a solution of this eddy-current problem which is developed in this paper.

Arguments more appropriate to field theory than to circuit theory lead to a classical boundary-value problem which takes into account the nature and thickness of the shell and the length of overhang, and provides formulae for current densities, flow lines and dissipated power in terms of ordinary machine parameters and the dimensions and electrical constants of the shell. Theoretical and practical results are compared and shown to be in close agreement. Some of the graphical results display a pronounced slot effect and suggest methods for making a more detailed investigation.

The theory can be extended to correspond to a composite shell of complex structure and it has some bearing on the principles employed in drag-cup motors, to which it could be applied.

(1) INTRODUCTION

Many of the technical difficulties encountered in the design of nuclear reactors and associated equipment arise from the particularly stringent safety precautions which must be observed. In circulating systems containing liquid metals, for example, the demand for a completely leak-proof enclosure focuses attention less on the provision of more reliable glands and seals than on avoiding them altogether. One solution—perhaps the most obvious—employs a centrifugal pump driven by a squirrel-cage motor. Both the pump and the rotor are totally enclosed and separated from the stator by a thin cylindrical conducting shell which is situated in the air-gap of the motor and effectively forms part of the wall of the sealed circulating system. The problem to be discussed here is essentially an electrical one, and no attempt will be made to discuss the mechanical and thermal problems which such an arrangement poses.

The merits of the arrangement for its particular purpose are obvious enough, for all the electrical windings and connections can be completed externally. That there are also disadvantages is equally clear, for a stationary conducting shell in a rotating magnetic field will lead to substantial eddy-current losses and reduced efficiency. In most respects except this, the design of such machines does not depart significantly from established practice, and the chief difficulty lies in predicting these losses about which there is little experience and even less information. The problem presented to the authors was to establish reliable information on this particular topic.

The conducting shell, in practice, is not terminated at the ends of the air-gap; it will not necessarily be made of the same material, and will certainly not have the same thickness as the rest of the circulating system of which it forms a part. The value of any theoretical solution depends on the success with which a compromise can be achieved between the facts as they exist and the account which can reasonably be taken of them. The composite shell is found to be more amenable to analysis than there is reason to hope or expect at the outset.

(2) THEORETICAL RESULTS

(2.1) General

Reduced to its simplest terms, the problem is one of relative motion between a magnetic field and a thin conducting sheet, and it therefore seems appropriate to seek a solution in terms of field theory rather than to employ circuit concepts.

It will be assumed that the flux density in the air-gap is radial and forms a travelling wave which varies sinusoidally in both space and time, and—at least in the first instance—it will also be assumed that the flux does not vary with axial position inside the air-gap and that it is zero elsewhere. This presumes a discontinuity in the flux at the end of the air-gap or, in other words,

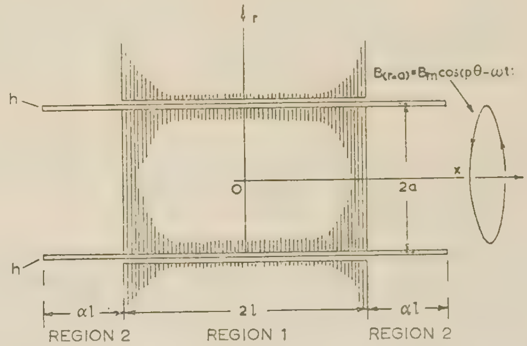

Fig. 1.—Open-ended shell with symmetrical overhang.

neglects fringing. Thus in Fig. 1, for $|x| \leqslant l$, i.e. in region 1, the radial flux cutting the shell can be represented by

$$B_{(r=a)} = B_m \cos(p\theta - \omega t) \quad . \quad . \quad . \quad . \quad (1)$$

whereas for $|x| \geqslant l$, in particular in the overhang region 2 where the shell extends beyond the magnetic stampings, it is taken as zero. The number of pole pairs on the stator winding is p, ω is the angular frequency of the supply, and θ is, with the usual conventions, the angular co-ordinate with respect to the x- and r-directions. The cylindrical shell, as shown in Fig. 1, is attached to the rotor, whereas in practice it will be fixed to the machine stator. The inverted arrangement is preferred for the ease with which the power loss in the shell can be determined by measuring the torque on the rotor at standstill. Finally, the shell thickness h will be taken as sufficiently small compared with its mean radius a for the radial variations of all quantities to be neglected. The last condition effectively reduces the

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
The authors are in the Electrical Engineering Department, University of Bristol.

problem to one in two variables, but as it does not possess circular symmetry there is a choice between cylindrical polar co-ordinates with respect to a cylinder of fixed radius a, and Cartesian co-ordinates with respect to the equivalent developed plane rectangular sheet, as illustrated in Fig. 2. In much of what

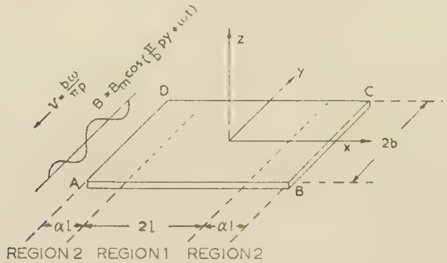

Fig. 2.—Planar form of the cylindrical diagram shown in Fig. 1.

follows the latter system has been chosen as being possibly the more familiar, but it could equally well have been the former, and formulae will be transposed freely between the two systems simply by using the relations $\pi a = b$ and $y = -a\theta$ as required. The first merely expresses the fact that BC, the width of the strip in the developed diagram (Fig. 2), is equal to the circumference of the original cylinder (Fig. 1). The negative sign is required in the second expression to preserve the convention for a right-hand system of axes in the two cases. The travelling flux-wave in the region $|x| \leqslant l$ in Fig. 2, for example, can be written

$$B_z = B_m \cos\left(\frac{\pi}{b}py + \omega t\right) \quad . \quad . \quad . \quad . \quad (2)$$

There are no discontinuities in the circumferential direction in the cylindrical problem. No end conditions therefore need be imposed along AB and CD in Fig. 2, or, what amounts to the same thing, ABCD can be regarded as part of a continuous strip of indefinite length in the y-direction.

(2.2) Particular Case: Conducting Shell with Zero Overhang and Zero-Resistance End-Rings

(2.2.1) Current Density.

If the magnetic field is regarded as being fixed in space and time and the cylindrical shell as rotating in the negative direction of θ with angular velocity (ω/p), the impressed electric field $\boldsymbol{E}$ established at any point in the shell can be deduced from Lorentz's equation, $\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B}$. Since the flux $\boldsymbol{B}$ has a z-component only and $\boldsymbol{v}(= a\omega/p)$ has a circumferential component only, it follows that $\boldsymbol{E}$ is wholly in the x-direction. Thus

$$E_x = \left(\frac{a\omega}{p}\right)B_m \cos(p\theta - \omega t) \quad . \quad . \quad . \quad . \quad (3)$$

which is clearly the same at all points on any line in the shell parallel to the x-axis. Subject to the assumptions previously prescribed this result is quite general.

Zero overhang means $\alpha = 0$ (Figs. 1 and 2), and by zero-resistance end-rings it is implied that the ends of the cylinder, or the sides AD and BC of the plane sheet, are equipotentials. As a consequence of this, and the direction of the impressed electric field E_x [eqn. (3)], the current flow is parallel to the x-axis at all points, but it does not of course have the same magnitude and sign everywhere. Further, for linear parallel current paths it follows, in effect from Kirchhoff's law, that the current density J_x is constant along any particular line which is parallel to the x-axis. The voltage gradient E_c arising from the flow of current is in the same direction as J_x and the relation $J_x = \sigma E_c$, where σ is the shell conductivity, shows that E_c is also constant along any line parallel to the x-axis. The impressed electric field $\boldsymbol{E}$ can therefore be equated to the voltage gradient E_c at every point, and from eqn. (3),

$$J_x = \left(\frac{\sigma a\omega}{p}\right)B_m \cos(p\theta - \omega t) \quad . \quad . \quad . \quad . \quad (4)$$

(2.2.2) Power Loss.

The total power dissipated is completely determined by evaluating the integral of J^2/σ throughout the volume of the shell. A less obvious method, but one which provides a much simpler alternative in the general case, is to integrate $\boldsymbol{J} \cdot \boldsymbol{E}$, that is the product of current density and the impressed electric field, throughout the shell. Since $\boldsymbol{E} \equiv (E_x, 0\ 0)$ for $|x| \leqslant l$ and is zero for $|x| \geqslant l$, it is only necessary even in the general case to consider the x-component of the current density, and the integration need be conducted only over that part of the shell within the air-gap. In circuit terms, this is tantamount to the assertion that if the e.m.f. of a source and the current through it are known then the power supplied, and hence the power dissipated, is completely specified without reference to the details of the circuit or the subsequent distribution of the current.

In the very special case discussed in this Section there is not much to choose between the two methods since J_x happens to be the total current. This will not always be so and to evaluate J^2/σ everywhere requires each component of current to be integrated over the whole shell and not over the central part only.

Substituting in $\boldsymbol{J} \cdot \boldsymbol{E}$ for E_x and J_x from eqns. (3) and (4),

$$P_0 = 2\sigma\left(\frac{a\omega B_m}{p}\right)^2 \int_0^{2\pi}\int_0^l \cos^2(p\theta - \omega t) h a d\theta dx$$

$$= \frac{2\pi\sigma h\omega^2 a^3 B_m^2 l}{p^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

or, in the Cartesian notation of Fig. 2,

$$P_0 = \frac{2\sigma h\omega^2 b^3 B_m^2 l}{\pi^2 p^2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

(2.3) The General Problem

If the shell is open-ended instead of short-circuited at the ends as discussed in Section 2.2, the current ceases to flow in the simple parallel straight lines used in Section 2.2.1 and the flow pattern becomes more complicated. It is precisely the difficulty of determining the current paths explicitly which leads to uncertainty in many eddy-current problems.

A further complication is introduced when it is remembered that, in practice, the shell will extend beyond the air-gap and that in pressure systems the overhang sections, which are not supported by the iron core, will probably be thicker than the inner section or fitted with backing-up rings.[1] In addition, there is no reason to suppose that the walls of the main circulating system and the conducting shell will necessarily be made of the same material or have the same thickness. Finally, unless the shell is insulated from its supporting member, some allowance should be made for the magnetic stampings, which provide a lower-resistance path to circumferential-current flow than to currents which flow in the axial direction. The shell therefore behaves over its central part as a non-isotropic conductor with different conductivities in the axial and circumferential directions.

In one way or another, these conditions can be allowed for. Indeed, in order to preserve a formal algebraic symmetry in the equations, it is convenient to consider a more general situation

Table 1

CURRENT DENSITIES IN AN OPEN-ENDED SHELL OF UNIFORM THICKNESS AND CONDUCTIVITY

OVERHANG COEFFICIENT: $\lambda = \tanh \frac{pl}{a} \tanh \alpha \frac{pl}{a}$

Central region: half-length l. $0 \leqslant x(=x_1) \leqslant l$	Overhang region: length αl. $l \leqslant x(=x_2) \leqslant (1+\alpha)l$
$J_{x1} = \left(\frac{\omega\sigma a B_m}{p}\right) \cos(p\theta - \omega t)\left[1 - \frac{\cosh \frac{p x_1}{a}}{(1+\lambda)\cosh \frac{pl}{a}}\right]$	$J_{x2} = -\left(\frac{\omega\sigma a B_m}{p}\right) \cos(p\theta - \omega t)\left\{\frac{\sinh \frac{p}{a}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda}\right)\sinh \frac{\alpha p l}{a}}\right\}$
$J_{\theta 1} = -\left(\frac{\omega\sigma a B_m}{p}\right) \sin(p\theta - \omega t)\left[\frac{\sinh \frac{p x_1}{a}}{(1+\lambda)\cosh \frac{pl}{a}}\right]$	$J_{\theta 2} = -\left(\frac{\omega\sigma a B_m}{p}\right) \sin(p\theta - \omega t)\left\{\frac{\cosh \frac{p}{a}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda}\right)\sinh \frac{\alpha p l}{a}}\right\}$

$x = 0$ $\qquad$ $x = l$ $\qquad$ $x = (1+\alpha)$

Table 2

CURRENT DENSITIES IN A CONDUCTING SHELL OF UNIFORM THICKNESS WITH ZERO-RESISTANCE END-RINGS

OVERHANG COEFFICIENT: $\lambda' = \frac{\tanh pl/a}{\tanh \alpha pl/a}$

Central region: half-length l. $0 \leqslant x(= x_1) \leqslant l$	Overhang region: length αl. $l \leqslant x(= x_2) \leqslant (1+\alpha)l$
$J'_{x1} = \left(\frac{\omega\sigma a B_m}{p}\right) \cos(p\theta - \omega t)\left[1 - \frac{\cosh \frac{p x_1}{a}}{(1+\lambda')\cosh \frac{pl}{a}}\right]$	$J'_{x2} = \left(\frac{\omega\sigma a B_m}{p}\right) \cos(p\theta - \omega t)\left\{\frac{\cosh \frac{p}{a}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda'}\right)\cosh \frac{\alpha p l}{a}}\right\}$
$J'_{\theta 1} = -\left(\frac{\omega\sigma a B_m}{p}\right) \sin(p\theta - \omega t)\left[\frac{\sinh \frac{p x_1}{a}}{(1+\lambda')\cosh \frac{pl}{a}}\right]$	$J'_{\theta 2} = \left(\frac{\omega\sigma a B_m}{p}\right) \sin(p\theta - \omega t)\left\{\frac{\sinh \frac{p}{a}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda'}\right)\cosh \frac{\alpha p l}{a}}\right\}$

$x = 0$ $\qquad$ $x = l$ $\qquad$ $x = (1+\alpha)l$

than is required for the laboratory tests. The expressions for current density displayed in Tables 1 and 2 are particular cases deduced from the general results in Section 7.2 and 7.3, and correspond to an insulated shell of uniform thickness and conductivity. By an insulated shell is meant one which does not make electrical contact with the magnetic stampings.

Suffixes 1 and 2 are used to refer to the central and overhang regions of the shell respectively. Thus x_1 denotes the x-co-ordinate of a point in region 1; a point in region 2 is denoted by x_2. Of the two analytical solutions which have been developed, one refers to an open-ended shell and the other to a shell which is closed by zero-resistance end-rings or plates. A dash against a symbol will be used henceforth to indicate that it refers specifically to the second of these two cases.

The parameters λ and λ', which are functions of the length of overhang, are called overhang coefficients. They are not the same, although they both tend to the same value, $\tanh pl/a$, for large values of α. Thus, for large overhangs the power loss is the same whether the shell is closed or open-ended. This is physically reasonable for it makes little difference whether the vanishingly small current which reaches the ends is supplied with a large or a small resistance when it gets there.

For small values of overhang, however, α is small and $\lambda \to 0$

Table 3

POWER LOSS IN CONDUCTING SHELL OF UNIFORM THICKNESS AND CONDUCTIVITY

Open-ended shell ..	$P = P_0\left[1 - \frac{\tanh \frac{p}{a} l}{\left(\frac{pl}{a}\right)(1+\lambda)}\right] = P_0 K_s$
Shell with zero end-resistance	$P' = P_0\left[1 - \frac{\tanh \frac{p}{a} l}{\left(\frac{pl}{a}\right)(1+\lambda')}\right] = P_0 K'_s$

whereas $\lambda' \to \infty$. Both J_{x2} and $J_{y2} \to 0$, as they should for an open-ended shell, whereas for a closed shell $J'_{y2} \to 0$ and $J'_{x2} \to J'_{x1}$, which is also reasonable. The fact that, in the limit, J'_{y1} disappears and J'_{x1} is constant might be regarded as an alternative proof of the conclusions deduced by other arguments in Section 2.2.

Expressions for power loss in the shell are shown in Table 3. Using the method outlined in Section 2.2.2 they are obtained almost by inspection from the tabulated values of J_{x1} and J_{x2} and the values of E_x given by eqn. (3), or they can be deduced from the general result in Sections 7.2 and 7.3. It will be noticed that the power is expressed as the product of a common electrical term P_0 and a non-dimensional quantity which is a function of the geometry of the system and will be denoted by K_s and K'_s. Both K_s and $K'_s \leqslant 1$—hence the term 'reduction factor' by which they were labelled in an earlier paper.[1]

(2.4) Flow Lines

Useful though the flow patterns are in presenting a visual picture of what is taking place, they are not usually the first things a designer would call for, although one paper on this topic[1] uses graphical flux-plotting techniques to estimate the flow pattern and then deduces useful design information from it.

The actual pattern of current flow will be one which travels around the surface of the cylinder, but it will be sufficient to consider any particular instant of time, say $t = 0$, to study the flow lines. For a field with p pole-pairs the complete pattern can be subdivided into $2p$ independent parts. The current flow is in opposite directions in adjacent parts, but the sub-patterns are otherwise identical, and any one can be taken as typical of the rest.

In an analytical sense the flow lines are completely specified by the relation

$$\frac{dy}{dx} = \frac{J_y}{J_x} \qquad \ldots \ldots \quad (6a)$$

When this equation has an exact solution, it gives information about a problem in finer detail than is readily obtainable by other methods and, as shown later, it also provides another way of comparing prediction and performance.

Equations to the flow lines in Cartesian co-ordinates at $t = 0$ for a uniform shell are given in Table 4. The quantities K in that Table are constants of integration, and different values correspond to different flow lines which can be plotted as functions of x and y in the ordinary way. For the maximum amount of information to be revealed, some discrimination must be exercised in the choice of values for K. Perhaps the most useful condition to impose is that the distance between neighbouring flow lines should correspond to the same current flow. By analogy with similar curves in electrostatics the pattern thus derived could be described as being composed of tubes of current. It is possible to assign significance to the strength of such tubes by expressing the flow per tube as a fraction of the total current flow in the pattern. It is fairly easy to find an algebraic expression for K as a condition for a particular flow line to divide the rectangular pattern area into two parts so that any given fraction (m/n) of the total current lies outside it. Table 5 gives the values of K to be used in the expressions in Table 4 in terms of (m/n) and the system constants. If the number of tubes required per pattern is n, successive members are obtained by putting $m = 1, 2, 3 \ldots (n - 1)$ in turn. The closeness or otherwise of the resulting lines gives a clear visual indication of the surface distribution of current.

Table 4

EQUATIONS TO THE FLOW LINES AT $t = 0$ FOR A UNIFORM SHELL WITH OVERHANG

	Central region: half-length l. $0 \leqslant x_1 \leqslant l$	Overhang region: length αl. $l \leqslant x_2 \leqslant (1 + \alpha)l$
Open-ended shell	$\sin\frac{\pi}{b}py\left[(1+\lambda)\cosh\frac{\pi}{b}pl - \cosh\frac{\pi}{b}px_1\right] = K_1$	$\sin\frac{\pi}{b}py\left\{\sinh\frac{\pi}{b}p[x_2 - (1+\alpha)l]\right\} = K_2$
Shell with zero-resistance end-rings	$\sin\frac{\pi}{b}py\left[(1+\lambda')\cosh\frac{\pi}{b}pl - \cosh\frac{\pi}{b}px_1\right] = K'_1$	$\sin\frac{\pi}{b}py\left\{\cosh\frac{\pi}{b}p[x_2 - (1+\alpha)l]\right\} = K'_2$

Table 5

VALUES OF K TO BE USED IN THE EXPRESSIONS FOR THE FLOW LINES IN TABLE 4 WHERE n IS THE NUMBER OF TUBES REQUIRED AND $m = 1, 2, 3, \ldots, (n - 1)$

Open-ended shell	$K_1 = \left(\frac{m}{n}\right)\left[(1+\lambda)\cosh\left(\frac{\pi}{b}pl\right) - 1\right]$	$K_2 = -(K_1)\left(\dfrac{\cosh\frac{\pi}{b}p\alpha l}{\sinh\frac{\pi}{b}pl}\right)$
Shell with zero-resistance end-rings ..	$K'_1 = \left(\frac{m}{n}\right)\left[(1+\lambda')\cosh\left(\frac{\pi}{b}pl\right) - 1\right]$	$K'_2 = (K'_1)\left(\dfrac{\sinh\frac{\pi}{b}p\alpha l}{\sinh\frac{\pi}{b}pl}\right)$

(3) PRACTICAL TESTS

(3.1) Torque and Power

(3.1.1) Test Equipment.

A 2-pole 3-phase 410–440-volt 0·5 h.p. induction motor of ordinary commercial quality and construction was employed for the torque tests. Both stator and rotor cores had a length

of 9·0 cm and, by turning down the rotor, the air-gap was increased to about 0·056 cm in order to accommodate the conducting shell. To avoid enhanced rotor losses, the rotor bars were removed, and two of the empty closed slots were used to hold a full-pitched search coil for measuring the flux in terms of the induced e.m.f. It was subsequently found that the flux thus measured was 3% less than the air-gap flux at the surface of the shell.

The conducting shells when attached to the rotor had a mean radius of 4·72 cm, and various lengths of overhang were used up to a maximum of 5·08 cm, which was determined by the position of the end-bells. A thermocouple was attached to the surface of the shell in a position just outside the rotor core.

The material used for the shell was commercial half-hard brass sheet (B.S. 265); 63% copper, 37% zinc, 0·039 cm thick. Measured values of resistivity and temperature coefficient were $6\cdot9 \times 10^{-6}$ ohm-cm at 40°C and $1\cdot5 \times 10^{-3}$ per deg C at 0°C respectively. The brass sheet was cut to size and bent to shape, and a soldered butt joint was made when it was clamped tightly to the rotor. This ensured something like a shrink fit; indeed some of the joints failed on cooling owing, no doubt, to the hoop stresses set up. A layer of adhesive was used between the rotor and the shell for all the tests in order to insulate the two.

To simulate a shell with zero end resistance and zero overhang, in an attempt to measure P_0 directly, heavy circular brass end-plates, 0·95 cm thick, were soldered at the ends. It was not physically possible to reduce the overhang, including the end-plates, to less than 1·97 cm (see Fig. 5).

(3.1.2) Procedure and Results.

The theoretical expressions are derived for a conducting surface which is stationary with respect to a travelling sinusoidal field and corresponds, therefore, to the practical situation in which the cylindrical shell is fixed to the stator of the induction motor. No significant changes are introduced when the shell is attached to the rotor, provided that it is prevented from rotating; this arrangement is preferred for test purposes, for the rotor torque at standstill is then a direct measure of the power transferred across the air-gap. This is not strictly true if the flux has a large harmonic content, for all the harmonic torques do not act in the same direction. To show that there was no error on this account, it was verified that the transferred power, determined from torque measurements, did not differ significantly from the difference between the stator losses and the total power input. In the absence of rotor bars the transferred power is almost wholly dissipated in the shell except for a small part due to hysteresis and eddy-current losses in the rotor stampings. These are easily measured by repeating the torque tests under similar flux conditions but with the shell removed. The difference between corresponding readings is then a measure of the additional power required due solely to introducing the shell.

Experience showed that sufficiently low-resistance end-plates were bulky and, in addition to the associated constructional problems, led to difficulty in estimating the length of overhang and uncertainty in the reliability of the results obtained. With one exception, therefore, all tests were performed on open-ended shells.

For a given machine and shell material there are three quantities which can be varied experimentally: ω, B_m and the overhang length αl. For a particular value of overhang, the power is directly proportional to P_0 or, from eqn. (5), since power transfer across the air-gap is the product of torque and synchronous angular velocity,

$$T \propto \omega\sigma B_m^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The temperature necessarily varied with changes in dissipated power, but, since the torque is directly proportional to the conductivity, it was a simple matter to adjust all torque readings to correspond to 40°C. The correction did not exceed 2%.

Fig. 3 shows graphs of measured torque as a function of the

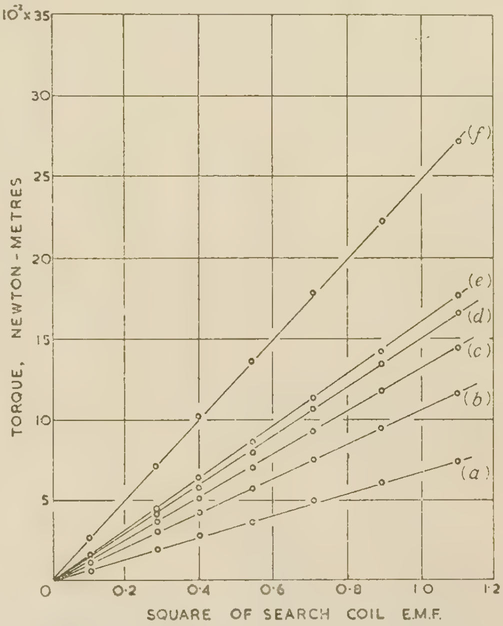

Fig. 3.—Variation of observed torque with the square of the flux density (in terms of the search-coil e.m.f.) at 50 c/s for different values of symmetrical overhang.

Results (*a*)–(*e*) are for an open-ended shell: (*f*) is for low-resistance end-rings, as shown in Fig. 5.

	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
α	0	0·29	0·57	0·86	1·14

flux density squared, in terms of the search-coil e.m.f., for different values of overhang at a constant frequency of 50 c/s. All the lines are straight, as they should be, and there is very little scatter.

Fig. 4 is a graph of torque against frequency for different values of overhang and for a constant flux, namely that which produces a search-coil e.m.f. of 1·0 volt at 50 c/s. Except for the zero-overhang line, which shows a slight curvature, all the graphs are linear, as demanded by theory, and again there is very little scatter.

Ignoring the constant of proportionality, Figs. 3 and 4 effectively verify the general form of the relation set out in eqn. (7).

A direct comparison between theoretical and observed values of power, expressed as fractions of P_0, is shown to scale in Fig. 5 for different values of overhang. The agreement is most satisfactory and would be almost exact if the value of P_0 were to be increased by about 4%. There is a very strong presumption therefore that the error does in fact reside in the estimation of P_0 and that the geometrical term in the expression for P in Table 3 very closely represents the nature of variation with overhang. The dotted theoretical curve is for a shell length less than l and the point R is the observed result for a short shell. Short shells are not likely to be encountered in practice. The low-resistance end-plates, one of which is shown in Fig. 5, were only used for the results plotted at S, and in all other cases the shell was open-ended.

To calculate P_0 from eqn. (5), a knowledge of B_m is required. This was deduced from measured r.m.s. values of the search-coil e.m.f. after applying a small leakage correction, determined in a separate test, to convert search-coil flux to air-gap flux. Even

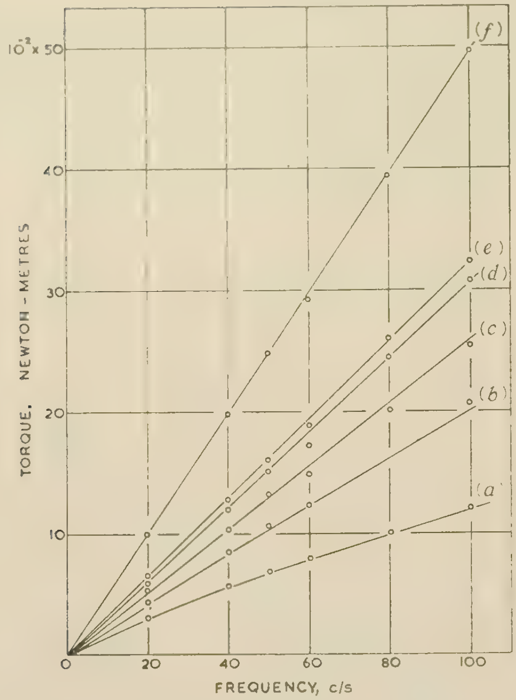

Fig. 4.—Variation of observed torque with frequency for different symmetrical overhangs and constant flux density.

Results (*a*)-(*e*) are for an open-ended shell: (*f*) is for low-resistance end-rings as hown in Fig. 5.

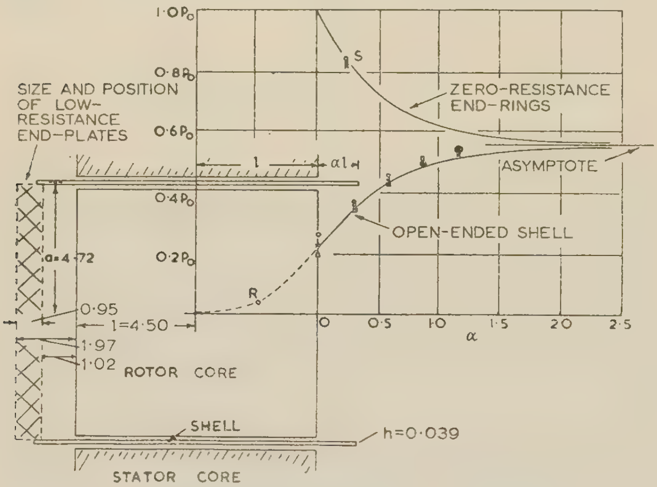

Fig. 5.—Theoretical and practical results for the power dissipated in a conducting shell with symmetrical overhang.

Two low-resistance end-plates, only one of which is shown in the diagram, were used for the results plotted at S. In all other tests the shell was open-ended. The point R is for a shortened shell. Dimensions are in centimetres.

□ □ □ 100 c/s, × × × 50 c/s, ○ ○ ○ 20 c/s.

so, because of slot effect, the e.m.f. was not independent of rotor position, and there was some uncertainty, therefore, about the value to be used in the calculation.

(3.2) Flow Lines

To find the flow lines in practice proved to be less difficult than had been supposed. The first task was to secure a stationary pattern identical in shape and form to the rotating pattern which ordinarily exists. This can be done by putting one phase of a 3-phase winding in series with the two others in parallel, and connecting a single-phase supply across the ends to produce a stationary pulsating field. The equal but oppositely rotating fluxes, to which this is equivalent, produce in the shell similar but oppositely rotating flow lines which combine to give a standing-wave pattern in the usual way.

For this particular test the pulsating field was established directly in a 4-pole 3-phase wound rotor of large physical dimensions, which was carefully insulated from the surrounding conducting shell. Since the normal flux distribution at points very close to the rotor surface, which is all that matters for present purposes, is not much affected by the stator iron, the latter can be dispensed with, thus leaving the whole of the outer surface of the shell free for measurement purposes.

Corresponding to the eddy currents in the shell there will be a surface distribution of electric intensity $\boldsymbol{J} = \sigma \boldsymbol{E}$ which can be explored by using a double probe unit with two points A and B a fixed distance apart (1·0 cm) and connected to a high-impedance voltage indicator such as an oscillograph or valve voltmeter. It is important to eliminate additional e.m.f.'s arising from flux linkages in the probe circuit. By careful design, it is possible so to reduce the effective area of the probe unit and connecting leads that the pick-up is negligibly small, even in the strongest parts of the magnetic field. The direction of $\boldsymbol{E}$ which defines the flow lines is that in which the reading is a maximum. Thus, by selecting any position Q, say, on the surface and swinging the probe unit like a pair of dividers alternately about its two points A and B, it is possible to mark out successive points at 1·0 cm spacings on the same flow line through the original chosen point. The orthogonals or the lines of zero work—they are not equipotentials in the usual sense of the term—can be plotted by using the same technique to seek the zero-voltage locus. These two sets of curves were plotted independently in different sectors on the surface and when superimposed were very closely orthogonal.

The axial lines along which J_y is zero and which divide the complete pattern into four, $2p$, identical parts were easily found, and by properly positioning the shell with respect to any one of these, the soldered butt-joint which was essential in earlier tests could be dispensed with.

It is sufficient to compare observed and calculated results in one quadrant of a sub-pattern, and this is done in Fig. 6. The

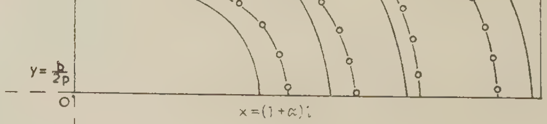

Fig. 6.—Theoretical and observed flow lines (not to scale) in one quadrant of a sub-pattern for a 4-pole field and an open-ended shell with symmetrical overhang.

theoretical curves were found by putting $n = 5$, and $m = 1, 2, 3, 4$, in turn in the equations to the flow lines, as explained in Section 2.4. The curves necessarily coincided at D_1, D_2, D_3, D_4, for these were used as starting-points for plotting the experimental lines. The general tendency for corresponding curves to separate

must be viewed with the cumulative error inherent in the method of plotting in mind. The biggest departures are not large, and they are obtained after not less than eight, and in one case sixteen, successive steps of the probe. In addition, there is a disturbance in the central region owing to the rotor slots, as is shown more clearly in Fig. 7. Finally, owing to differences in

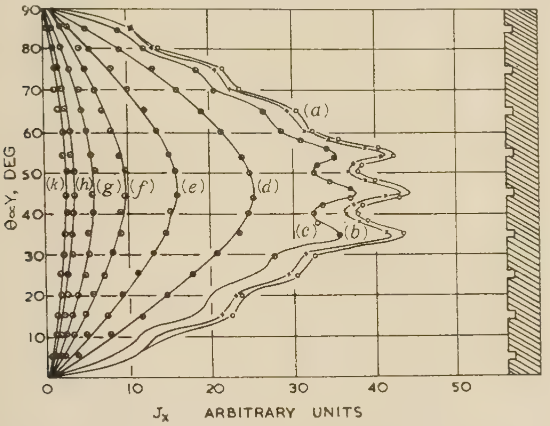

Fig. 7.—Variation of J_x with y or θ for different values of x.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(k)
x	0	1	2	3	4	5	6	7	8
x/l	0	0·33	0·67	1·00	1·33	1·67	2·00	2·33	2·67

The shaded area illustrates the position of the rotor slots which are directly related to the irregularities in curves (a), (b) and (c), corresponding to the central region 1. There are no irregularities for the curves in the overhang section. To distinguish between (a) and (b), crosses are used for the latter.

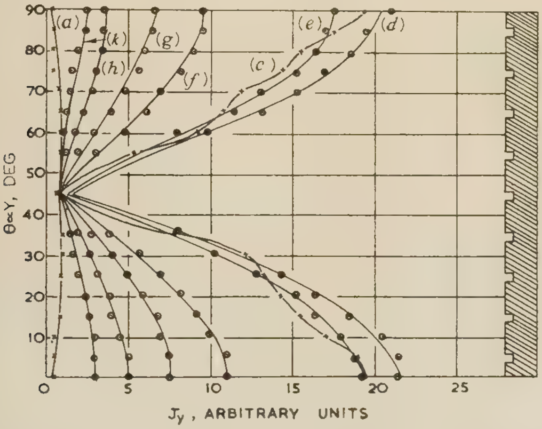

Fig. 8.—Variation of J_y with y or θ for different values of x.

	(a)	(c)	(d)	(e)	(f)	(g)	(h)	(k)
x	0	2	3	4	5	6	7	8
x/l	0	0·67	1·00	1·33	1·67	2·00	2·33	2·67

The shaded area illustrates the position of the rotor slots. Curves (a) and (c) correspond to the central region 1.

××× region (1). ○○○ region (2).

current densities in the shell and the heating effect of rotor currents, there were pronounced temperature differences corresponding roughly to the central region 1 and overhang region 2, where in addition convection cooling was more effective. As the general equation (37) shows, a decrease in conductivity in the central region gives an increased value of λ. The effect of this would be to displace the intercepts with the x-axis positively, and thus to diminish the difference between these curves in Fig. 6. It was not possible to get reliable readings near the kernel 0, for not only was the current density low, but the probe spacing of 1·0 cm was too coarse for the curvature of the lines in that region.

Developing the argument advanced above, that the voltage between the points A and B for any position of the probe unit is a measure of the electric intensity in the direction AB, it is possible to investigate the separate components of current density directly, for $J_x = \sigma E_x$ and $J_y = \sigma E_y$. To find the variation of J_x with y, for example, the probe unit is fixed so that AB is parallel to the x-axis. For J_y, the probe is fixed with the line AB parallel to the y-axis, and in each case in turn the rotor is moved through small angular steps, corresponding to the required increments of y, for different values of x. Figs. 7 and 8 were found in this way. The ordinates are expressed in degrees, but they are easily expressed in terms of y if required.

It so happened that it was possible to find the position of the rotor teeth with some precision, and, as shown in a quite remarkable fashion, the disturbances in Fig. 7 can be attributed to slot effect with more conviction than this explanation usually carries. Indeed, these curves could well be used for a more detailed analysis of the manner in which slot effects contribute to the total shell losses. It will be observed that the disturbances are absent in the overhang section. In the absence of rotor slots, all the curves in Figs. 7 and 8 should be sinusoidal in shape.

Fig. 9 shows observed and theoretical results for the variation

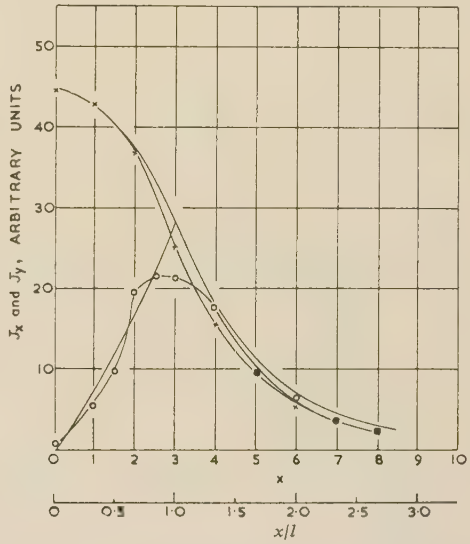

Fig. 9.—Comparison between theory and practice for variations of J_x and J_y with x.

Particular values of y were chosen to correspond to the maximum values of $\cos\frac{\pi}{b}py$ and $\sin\frac{\pi}{b}py$ for J_x and J_y respectively.

×××× J_x. ○○○○ J_y.

$p = 2$, $a = 11 \cdot 5$ cm, l (effective) $= 7 \cdot 62$ cm.

of J_x and J_y with x. The agreement between the J_x curves is good but between the J_y curves it is less satisfactory. This was not entirely unexpected, for the theory assumes the flux to change abruptly at the end of the stator core, whereas owing to fringing, assisted by a rather large conductor overhang in the rotor used, the change is much more gradual.

(4) DISCUSSION AND CONCLUSIONS

The open-ended shell and the shell with zero-resistance end-rings represent two clearly defined analytical limiting conditions corresponding to open- and short-circuit terminations respectively; between these two extreme conditions any practical problem will fall. There is a marked similarity in form throughout between expressions for corresponding quantities in the two cases, and a good agreement between theory and practice for the open-ended shell can be taken to confer the same order of

reliability on the theoretical results for the shell with zero-resistance end-rings, though the required end conditions could not be achieved in this case.

It is appropriate here to refer again to the paper[1] which derives by graphical means some of the results, particularly those relating to power loss, which are here expressed in analytical terms. The method, briefly, is to find constants K_s by which P_0 must be multiplied in order to give the power loss in the shell. The expression derived for P_0, the loss for zero overhang and zero-resistance end-rings, is substantially the same as that given by eqn. (5). A flux-plotting technique is then employed to find the flow lines and orthogonals for an open-ended shell with overhang, and the total I^2R loss is found, for comparison with P_0, by adding the contributions from each of the curvilinear rectangles. Clearly, the semi-empirical constants K_s obtained in this way for different values of pl/a correspond to the geometrical terms referred to in Section 2.3 and expressed in algebraic form in Table 3.

Fig. 10 is a graph of calculated values of K_s and K_s' against

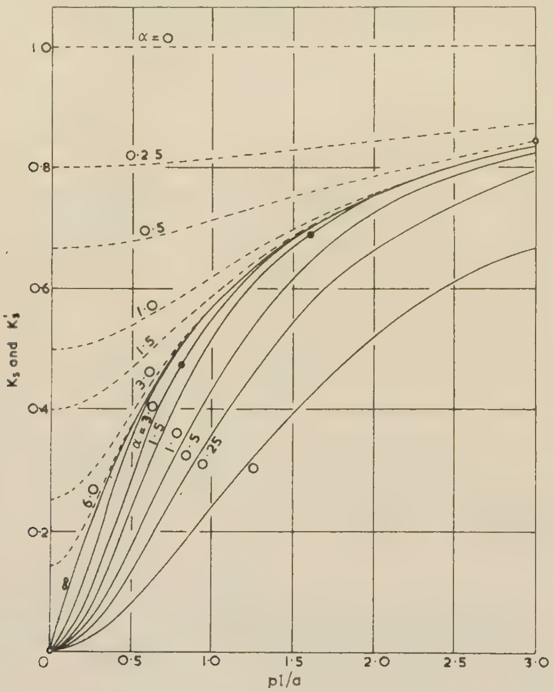

Fig. 10.—Variation of the non-dimensional parameters K_s and K_s' with (pl/a).

——— Open-ended shell.
— — — Zero-resistance end-rings.
○○○ Practical results from Reference (1).

pl/a for different values of overhang, and clearly the two systems of curves tend to the same limiting value as the overhang increases. It is equally clear from a few superimposed semi-empirical values that the latter all lie near the limiting locus. The good agreement between theory and practice which the paper claims when the power loss is 'substantially independent of the amount of end extension' thus provides corroborative support for the analytical results, but the empirical values of K_s quoted are not likely to be so satisfactory in other cases when the overhang is not limitingly large.

The chief problem in design is to minimize the shell losses, and the most obvious way is to reduce P_0 [eqn. (5)]. The shell will in any event be as thin as possible, consistent with adequate mechanical strength, and as the shaft speed will usually be determined by the pumping requirements, ω/p will be predetermined. A low-conductivity material is obviously desirable, but all likely insulating materials—ceramics have been considered—react chemically with the circulating fluid, and corrosion-resistant materials must be used. Thus effectively only l and a are open to choice.

On the evidence hitherto available, it has been supposed[2] that a motor with a large length/diameter ratio was desirable, but this is not necessarily so. Using the familiar result that the rating of a machine is determined by the rotor volume, Fig. 11

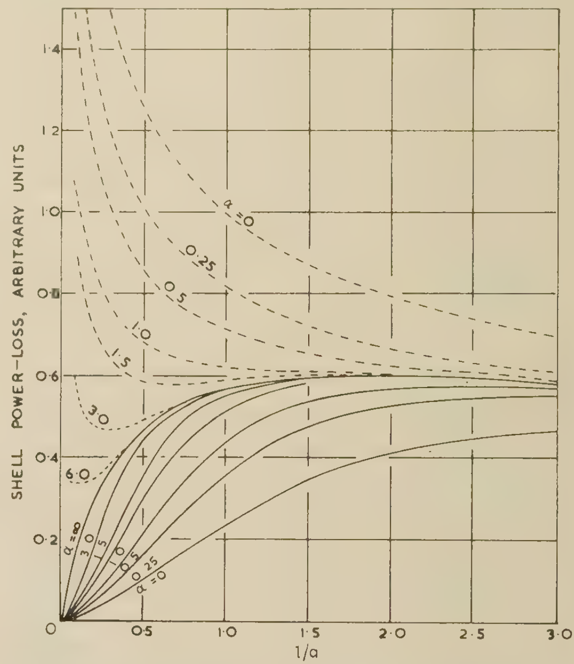

Fig. 11.—Variation of shell power-loss with the length/diameter ratio of the machine for a given rotor volume.

The power is expressed in arbitrary units, but a scale factor can be assigned fairly simply when it is noticed that the curve for zero-resistance end-rings and $\alpha = 0$ corresponds to values of P_0.

shows to an arbitrary scale how the power loss in the shell varies with l/a for different values of overhang, for a constant power input, and for a given frequency. The graphs have been drawn for $p = 1$, by way of example, but other pole numbers could equally well have been chosen.

It is true that for zero-resistance end-rings and zero or very small overhang, a large length/diameter ratio is accompanied by diminished shell losses. For quite moderate values of overhang, say $\alpha = 1$, however, the power loss becomes reasonably constant and the length/diameter ratio is unimportant providing it is greater than unity. Broadly the same conclusions can be formed for the open-ended shell, except that the losses tend to be larger rather than smaller for long machines.

These are not the only considerations, and other factors must be taken into account. For example, it may be found that for constructional or installation reasons the overhang length tends to be constant. A given value of overhang length for different machines corresponds to different values of α, and the graphs must be interpreted accordingly.

It is beyond the purpose of the present account to do more than suggest further developments. For example, it is sometimes necessary to enclose the rotor of the induction motor as a protection against corrosion. The rotor shell will of course have end plates, but they will not have zero resistance, and the overhang will be small. An estimate of the rotor shell loss could be obtained by inserting appropriate values in eqn. (44). The value

of P_0 will be given by eqn. (5), bearing in mind that the relative motion between field and shell will depend on the slip frequency in this case. It has, however, been estimated that the loss arising in this way is exceeded by that produced in the rotor shell by the effect of stator slots.[1]

The drag-cup motor is essentially a problem of a rotating cylindrical shell and the aim in this case is to secure maximum torque and hence a large shell loss. The principles developed here are believed to be simpler, more general, and more flexible in application than some which have been proposed.[3] When the drag-cup rotor is effectively open-ended, the formulae can be used directly, and Fig. 11 suggests that a large length/diameter ratio is preferred, but in some cases one end is closed and the other is open, and formulae appropriate to these end conditions will be required.

The original problem assumed equal overhang at the two ends of the shell, but it is not essential to do so, though asymmetry, whether of dimensions or conductivity, will necessarily lead to more complicated algebra.

Again at the price of complication, the analysis could be extended to a shell with more than two regions. In any overhang section, both J_x and J_y satisfy Laplace's equation. For travelling-wave solutions, the arguments of Section 7.2 show that two constants must be determined in each case, and for this purpose the two boundary conditions at each end of the section will suffice. An example of an extended problem of this sort would be a shell with a different gauge and material from the system in which it is included, though if heavy ring-welds were to be used at the ends it might well approach the simpler conditions for zero-resistance end-rings.

Current tests are being directed to finding the effect of insulating the shell from the stampings. This is not ordinarily done, and it remains to be seen whether or not the reduction in P is sufficiently substantial to warrant the complication when balanced against the heat problem, for the insulating layer will act as a thermal barrier also.

(5) ACKNOWLEDGMENTS

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(7) APPENDICES

(7.1) Formulation of the General Problem

Since the cylindrical conducting shell is thin compared with its mean radius, it can be developed into a flat strip for analytical purposes, with axes of reference as shown in Fig. 2. For the same reasons, there will be no significant change in conditions with variations in z within the conductor, i.e. $\partial/\partial z = 0$ and the problem can be treated as a 2-dimensional one in x and y.

There are no circumferential discontinuities in the cylindrical shell, and edge effects along AB and DC in Fig. 2 can therefore be ignored. The simple expressions ($\pi a = b$) and ($y = -a\theta$) are sufficient to establish formal relations between the cylindrical and plane co-ordinates.

It will be assumed that the magnetic field is zero except in the central region, of length $2l$, where it is parallel to the z-axis at all points and can be represented by

$$B \equiv (0, 0, B_z), \text{ where } B_z = B_m \cos\left(\frac{\pi}{b}py + \omega t\right) \quad . \quad (8)$$

Consider an elementary rectangle TUVW in the plane conductor, parallel to the z-plane and with sides dx and dy (see Fig. 12).

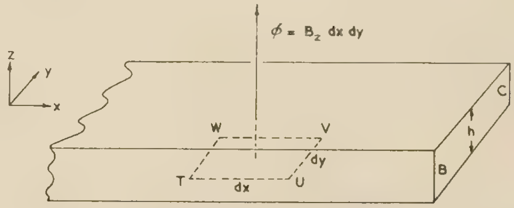

Fig. 12.—Path of integration in the xy-plane within the conducting sheet.

The line integral of electric intensity round TUVW in a right-hand sense with respect to the flux linking it is equal to minus the time rate of change of flux linkages:

$$E_{TU}dx + E_{UV}dy + E_{VW}dx + E_{WT}dy = \frac{-\partial\phi}{\partial t} = \frac{-\partial B_z}{\partial t}dxdy \quad . \quad . \quad . \quad . \quad (9)$$

or

$$E_x dx + \left(E_y + \frac{\partial E_y}{\partial x}\right)dy - \left(E_x + \frac{\partial E_x}{\partial y}\right)dx - E_y dy = \frac{-\partial B_z}{\partial t}dxdy \quad . \quad (10)$$

where E_x and E_y are the components of electric intensity at T.

It has been pointed out earlier that unless the shell is insulated from its supporting member the magnetic stampings will provide parallel paths for the circumferential currents, so that the effective circumferential conductivity will be greater than the conductivity for currents flowing in the axial direction. Such a conductor is said to be non-isotropic. The simple relation $J = \sigma E$ can no longer be used, but as the x- and y-directions happen to be the principal electrical axes it can be replaced by

$$J_x = \sigma_x E_x \quad \text{and} \quad J_y = \sigma_y E_y \quad . \quad . \quad . \quad (11)$$

Substituting for E_x and E_y in eqn. (10),

$$\frac{1}{\sigma_y}\frac{\partial J_y}{\partial x} - \frac{1}{\sigma_x}\frac{\partial J_x}{\partial y} = -\frac{\partial B_z}{\partial t} \quad . \quad . \quad . \quad . \quad (12)$$

No useful information is obtained by taking similar rectangles in the yz- and zx-planes. If the line integral of H round these elementary rectangles is evaluated, the differential equation which is ultimately obtained is the familiar 'heat flow' or 'skin effect' equation. This takes into account the local magnetic field of the eddy currents themselves. For a thin shell at low frequencies there will be complete penetration by the applied magnetic field,

and it is consistent with the assumption that B_z does not vary with z to ignore these effects.

A further condition which must be satisfied in all conductors is that div $J = 0$, i.e.

$$\frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Eliminating J_x and J_y in turn between eqn. (12) which is Faraday's law and eqn. (13) which is in effect Kirchhoff's law, or the equation of continuity, the following general differential equations are obtained:

$$\frac{1}{\sigma_y}\frac{\partial^2 J_x}{\partial x^2} + \frac{1}{\sigma_x}\frac{\partial^2 J_x}{\partial y^2} = \frac{\partial^2 B_z}{\partial y \partial t} \quad . \quad . \quad . \quad . \quad (14)$$

$$\frac{1}{\sigma_y}\frac{\partial^2 J_y}{\partial x^2} + \frac{1}{\sigma_x}\frac{\partial^2 J_y}{\partial y^2} = \frac{-\partial^2 B_z}{\partial x \partial t} \quad . \quad . \quad . \quad . \quad (15)$$

Using a suffix (1) to refer to the central region and substituting for B_z from eqn. (8),

$$\frac{1}{\sigma_{y1}}\frac{\partial^2 J_{x1}}{\partial x^2} + \frac{1}{\sigma_{x1}}\frac{\partial^2 J_{x1}}{\partial y^2} = -\left(\frac{\omega\pi p B_m}{b}\right)\cos\left(\frac{\pi}{b}py + \omega t\right) \quad . \quad (16)$$

$$\frac{1}{\sigma_{y1}}\frac{\partial^2 J_{y1}}{\partial x^2} + \frac{1}{\sigma_{x1}}\frac{\partial^2 J_{y1}}{\partial y^2} = 0 \quad . \quad . \quad . \quad . \quad (17)$$

Using suffix 2 to refer to the overhang region, where B_z is zero, eqns. (14) and (15) become

$$\frac{1}{\sigma_{y2}}\frac{\partial^2 J_{x2}}{\partial x^2} + \frac{1}{\sigma_{x2}}\frac{\partial^2 J_{x2}}{\partial y^2} = 0 \quad . \quad . \quad . \quad . \quad (18)$$

$$\frac{1}{\sigma_{y2}}\frac{\partial^2 J_{y2}}{\partial x^2} + \frac{1}{\sigma_{x2}}\frac{\partial^2 J_{y2}}{\partial y^2} = 0 \quad . \quad . \quad . \quad . \quad (19)$$

The reasons for supposing that σ_x and σ_y are different do not apply to the overhang regions, but to preserve algebraic symmetry it is better to proceed as though they do and then to impose the appropriate limiting conditions as required.

To make the problem more general it will be assumed that the shell thicknesses in regions 1 and 2 are different, and it is therefore necessary to apply the appropriate conditions at the boundary between them. They are two in number.

One of them asserts that the tangential component of electric stress at a boundary is continuous:

$$E_{y1} = E_{y2} \quad \text{or} \quad \frac{J_{y1}}{\sigma_{y1}} = \frac{J_{y2}}{\sigma_{y2}} \quad . \quad . \quad . \quad . \quad (20)$$

The other refers to the normal component of current and ensures that Kirchhoff's first law is not violated at the boundary:

$$h_1 J_{x1} = h_2 J_{x2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

where h_1 and h_2 are the thicknesses of the shell in regions 1 and 2 respectively.

Within the framework of the original assumptions the problem is completely specified by the information which is contained in eqns. (13) and (16)–(21).

The differential equations are sufficiently similar to Laplace's equation to suggest a change in variable in an attempt to cast them in the right form. Perhaps the most appropriate transformations in the present problem are those which leave y unaltered and change the x-co-ordinate according to the relations

$$x_1 = \sqrt{\left(\frac{\sigma_{x1}}{\sigma_{y1}}\right)}X_1, \quad x_2 = \sqrt{\left(\frac{\sigma_{x2}}{\sigma_{y2}}\right)}X_2 \quad . \quad . \quad (22)$$

where $0 \leqslant |x_1| \leqslant l$ and $l \leqslant |x_2| \leqslant (1+\alpha)l$.

The effect of making this substitution throughout in eqns. (13) and (16)–(21) is shown in Fig. 13, which is a concise summary of the mathematics of the problem. Capital letters denote transformed quantities.

It is true that J_{x1} is given by Poisson's equation, but it is easily shown that the particular integral is

$$\frac{\omega\sigma_{x1}bB_m}{\pi p}\cos\left(\frac{\pi}{b}py + \omega t\right)$$

and the remaining part of the solution, the complementary function, is then given by Laplace's equation.

In general, if the solution of

$$\frac{\partial^2 J}{\partial X^2} + \frac{\partial^2 J}{\partial y^2} = 0$$

can be expressed as a product of a function of X and a function of y, it is possible to separate the variables and to write the

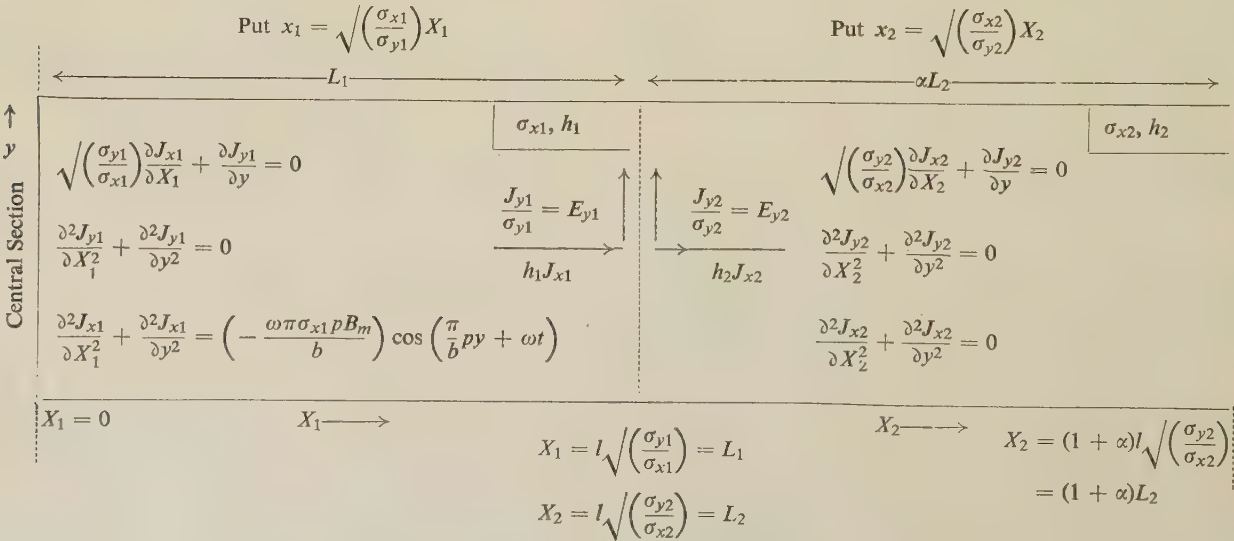

Fig. 13.—Analytical statement of the problem after transformation of the variable.

solution as some constant times the product of either $\sin(ny+\beta)$ or $\cos(ny+\beta)$ and either $\sinh(nX+\gamma)$ or $\cosh(nX+\gamma)$, as is explained in most textbooks on the subject. It is not of course necessary to consider all four possibilities, and for economy of algebraic effort in finding the constants n, β, γ, etc., the one which can be made to conform most naturally to the problem and its boundary conditions should be chosen.

It will be assumed that the overhang sections at the two ends are identical, and two particular cases will be discussed: one in which the shell is open-ended, and the other in which it is terminated with zero-resistance end-rings. The problem is symmetrical about $x=0$, and it is sufficient therefore to restrict the argument to positive values of x.

(7.2) Open-Ended Conducting Shell with Overhang

(7.2.1) Current Densities.

From the above J_{x1} can be written

$$J_{x1}=\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\cos\left(\frac{\pi}{b}py+\omega t\right)+G_1\cos(ny+\beta)\cosh(nX_1+\gamma) \quad . \quad (23)$$

From considerations of symmetry J_{x1} should be a maximum at $x_1=0$, that is when $X_1=0$, and should be unaffected by a change in sign of x_1. Therefore $\gamma=0$. Further, for a travelling-wave type of solution, which the problem demands, $n=\frac{\pi}{b}p$ and $\beta=\omega t$. Thus

$$J_{x1}=\cos\left(\frac{\pi}{b}py+\omega t\right)\left[\frac{\omega\sigma_{x1}bB_m}{\pi p}+G_1\cosh\left(\frac{\pi}{b}pX_1\right)\right] \quad . \quad (24)$$

For J_{x1} to be a maximum at the origin, J_{y1} must be zero there. Therefore the appropriate form for J_{y1}, to satisfy Laplace's equation, can be written

$$J_{y1}=F_1\sin(ny+\beta)\sinh nX_1 \quad . \quad . \quad . \quad (25)$$

In addition, both eqns. (24) and (25) must satisfy the equation of continuity, that is

$$\left(\frac{\pi}{b}p\right)\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}G_1\cos\left(\frac{\pi}{b}py+\omega t\right)\sinh\frac{\pi}{b}pX_1+F_1n\cos(ny+\beta)\sinh nX_1=0$$

for all y, t and $0\leqslant X_1\leqslant L_1$

and therefore $\qquad \sqrt{(\sigma_{x1})}F_1+\sqrt{(\sigma_{y1})}G_1=0 \quad . \quad . \quad . \quad . \quad (26)$

and, what might also be determined on inspection, $n=\frac{\pi}{b}p$ and $\beta=\omega t$.

Thus

$$J_{y1}=(-)\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}G_1\sin\left(\frac{\pi}{b}py+\omega t\right)\sinh\frac{\pi}{b}pX_1 \quad . \quad (27)$$

No current can leave the end of the shell in this case, and therefore in region 2 we have $J_{x2}=0$ when $X_2=(1+\alpha)L_2$. Therefore

$$J_{x2}=G_2\cos(ny+\beta)\sinh n[X_2-(1+\alpha)L_2] \quad . \quad (28)$$

Applying the boundary conditions $h_1J_{x1}=h_2J_{x2}$ at the barrier between the two regions, i.e. where $X_1=L_1$ and $X_2=L_2$, eqns. (24) and (28) give

$$h_1\cos\left(\frac{\pi}{b}py+\omega t\right)\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}+G_1\cosh\frac{\pi}{b}pL_1\right)=-h_2G_2\cos(ny+\beta)\sinh n\alpha L_2 \text{ for all } y \text{ and } t \quad . \quad (29)$$

Therefore

$$h_1G_1\cosh\frac{\pi}{b}pL_1+h_2G_2\sinh\frac{\pi}{b}p\alpha L_2=-\frac{h_1\omega\sigma_{x1}bB_m}{\pi p} \quad . \quad (30)$$

and, again, $n=\frac{\pi}{b}p$, $\beta=\omega t$. Thus

$$J_{x2}=G_2\cos\left(\frac{\pi}{b}py+\omega t\right)\sinh\frac{\pi}{b}p[X_2-(1+\alpha)L_2] \quad . \quad (31)$$

Similarly J_{y2} can be written

$$J_{y2}=F_2\sin(ny+\beta)\cosh(nX_2+\gamma) \quad . \quad . \quad (32)$$

and, from eqns. (31) and (32), applying the equation of continuity as before,

$$n=\frac{\pi}{b}p,\quad \beta=\omega t,\quad \left(\frac{\pi}{b}pX_2+\gamma\right)=\frac{\pi}{b}p[X_2-(1+\alpha)L_2]$$

and $\qquad \sqrt{(\sigma_{x2})}F_2+\sqrt{(\sigma_{y2})}G_2=0 \quad . \quad . \quad . \quad . \quad (33)$

Therefore

$$J_{y2}=(-)\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}G_2\sin\left(\frac{\pi}{b}py+\omega t\right)\cosh\frac{\pi}{b}p[X_2-(1+\alpha)L_2] \quad . \quad . \quad . \quad . \quad (34)$$

Again, applying the boundary condition $\frac{J_{y1}}{\sigma_{y1}}=\frac{J_{y2}}{\sigma_{y2}}$ for all y and t at the barrier between regions 1 and 2, eqns. (27) and (34) give

$$\frac{1}{\sigma_{y1}}\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}G_1\sinh\frac{\pi}{b}pL_1=\frac{1}{\sigma_{y2}}\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}G_2\cosh\left(\frac{\pi}{b}p\alpha L_2\right) \quad . \quad (35)$$

From eqns. (30) and (35)

$$h_1G_1(1+\lambda)\cosh\frac{\pi}{b}pL_1=h_2G_2\left(1+\frac{1}{\lambda}\right)\sinh\frac{\pi}{b}p\alpha L_2=-\left(\frac{\omega\sigma_{x1}h_1bB_m}{\pi p}\right) \quad . \quad (36)$$

where $\qquad \lambda=\frac{h_2}{h_1}\sqrt{\left(\frac{\sigma_{x2}\sigma_{y2}}{\sigma_{x1}\sigma_{y1}}\right)}\tanh\frac{\pi}{b}p\alpha L_2\tanh\frac{\pi}{b}pL_1 \quad . \quad . \quad (37)$

and $\qquad L_1=l\sqrt{\frac{\sigma_{y1}}{\sigma_{x1}}},\quad L_2=l\sqrt{\frac{\sigma_{y2}}{\sigma_{x2}}}$

Substituting these values of G_1 and G_2 in eqns. (24), (27), (31) and (34) and retransposing to the original co-ordinates using eqn. (22),

$$J_{x1}=\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\cos\left(\frac{\pi}{b}py+\omega t\right)\times\left[1-\frac{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1}{(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad . \quad (38)$$

$$J_{y1} = \sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\sin\left(\frac{\pi}{b}py + \omega t\right) \cdot \left[\frac{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1}{(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad . \quad (39)$$

$$J_{x2} = -\frac{h_1}{h_2}\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\cos\left(\frac{\pi}{b}py + \omega t\right) \times \left\{\frac{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda}\right)\sinh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}\right\} \quad . \quad (40)$$

$$J_{y2} = \left(\frac{h_1}{h_2}\right)\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\sin\left(\frac{\pi}{b}py + \omega t\right) \times \left\{\frac{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2 - (1+\alpha)l]}{\left(1+\frac{1}{\lambda}\right)\sinh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}\right\} \quad . \quad (41)$$

It might be observed that in all laboratory tests the shell was of uniform thickness and was insulated from the magnetic stampings. The appropriate formulae are deduced from eqns. (38)–(41) by putting $h_1 = h_2 = h$ and $\sigma_{x1} = \sigma_{y1} = \sigma_{x2} = \sigma_{y2} = \sigma$. The cylindrical forms of the expressions thus deduced are those set out in Table 1.

(7.2.2) **Power.**

In practice, a sinusoidal travelling wave moves past a stationary conductor, but the conducting strip could equally well be regarded as moving along the y-axis with velocity $\omega b/\pi p$ through a stationary magnetic field which does not vary with time and is sinusoidally distributed in space. Thus Lorentz's equation can be invoked to express the electric intensity set up at any point in the conductor. In general

$$\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B}$$

The rate at which energy is supplied to the conductor and hence the power dissipated is then found by evaluating the volume integral of $\boldsymbol{E} \cdot \boldsymbol{J}$ throughout the conductor. That is

$$P = \int\int\int \boldsymbol{E} \cdot \boldsymbol{J} dxdydz = h\int\int \boldsymbol{v} \times \boldsymbol{B} \cdot \boldsymbol{J} dxdy \quad . \quad (42)$$

where $\boldsymbol{v} \equiv (0, \omega b/p\pi, 0)$ and $\boldsymbol{B} \equiv (0, 0, B_z)$.

For zero values of B_z, the continuous vector product in eqn. (42) vanishes, and P exists therefore only for non-zero values of B_z, i.e. within the central region 1, where

$$B_z = B_m \cos\left(\frac{\pi}{b}py + \omega t\right)$$

and the corresponding current density is given by $\boldsymbol{J} \equiv (J_{x1}, J_{y1}, 0)$. Thus

$$(\boldsymbol{v} \times \boldsymbol{B} \cdot \boldsymbol{J}) = \begin{vmatrix} 0 & \frac{\omega b}{p\pi} & 0 \\ 0 & 0 & B_m \cos\left(\frac{\pi}{b}py + \omega t\right) \\ J_{x1} & J_{y1} & 0 \end{vmatrix} \quad . \quad . \quad . \quad (43)$$

and, using limits of integration and shell thickness corresponding to the central region 1 and substituting for J_{x1} from eqn. (38),

$$P = 2h_1\left(\frac{\omega b}{p\pi}B_m\right)^2 \sigma_{x1}\int_{-b}^{+b}\cos^2\left(\frac{\pi}{b}py + \omega t\right)dy \times \int_0^l \left[1 - \frac{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x}{(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right]dx$$

$$= P_0\left[1 - \frac{\tanh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}{\frac{\pi p}{b}\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}(1+\lambda)l}\right] \quad . \quad (44)$$

The value of P_0 here, in the notation appropriate to the general problem, is exactly the same as that derived in a more special case in eqn. (6). As before, the formulae appropriate to the laboratory tests are obtained by putting $h_1 = h_2 = h$ and $\sigma_{x1} = \sigma_{y1} = \sigma_{x2} = \sigma_{y2} = \sigma$. It is the cylindrical form of the expression thus obtained which is quoted in the top row of Table 3.

An alternative method would be to find the I^2R loss directly by evaluating the volume integral of $(J^2/\sigma)dxdydz$ throughout the conductor. This would necessarily be more complicated, for there would be four terms in the volume integral corresponding to the x- and y-components of current densities in both regions of the conductor, as given by eqns. (38)–(41), but the result would be exactly the same.

(7.2.3) **Flow Lines.**

The general differential equation to the flow lines is

$$\frac{dy}{dx} = \frac{J_y}{J_x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

Putting $t = 0$ in eqns. (38) and (39)—for there is no loss in generality in considering a particular instant of time—substituting in eqn. (45) and integrating, the flow lines at $t = 0$, in region 1, are given by

$$\sin\frac{\pi}{b}py\left[(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l - \cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1\right] = K_1 \quad . \quad . \quad . \quad . \quad (46)$$

Different values of the constant of integration K_1 give different flow lines.

Taking eqns. (38), (39), and (46) together it is easy to see that the complete pattern is composed of $2p$ similar parts, one quadrant of which is shown in Fig. 6.

Putting $x = 0$ in eqn. (39) shows that J_{y1} is zero for all y and t, and therefore the total current flow in the sub-pattern is obtained by integrating J_{x1} along OP. Similarly the current flow between some point Q and P is obtained by integrating J_{x1} between points Q and P. For the latter to be m/n of the current flow between O and P, where m and n are integers,

$$\frac{m}{n}\left[(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l - 1\right] = K_1 \quad . \quad . \quad (47)$$

Thus the flow line in region 1 which excludes m/nths of the current flow per sub-pattern is given by

$$\sin\frac{\pi}{b}py\left[(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l-\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1\right]$$
$$=\left(\frac{m}{n}\right)\left[(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l-1\right] \quad (48)$$

By taking $m = 1, 2, 3 \ldots (n-1)$ in turn in eqn. (48), the $(n-1)$ flow lines obtained will be such that the current flow between any two adjacent members will be $1/n$th of the total current flow in the sub-pattern. The lines could equally be said to define n current tubes of equal strength.

Employing precisely the same arguments with respect to J_{x2} and J_{y2} the flow lines in region 2 can be written

$$\sin\frac{\pi}{b}py\left\{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2-(1+\alpha)l]\right\}=K_2 \quad (49)$$

where, to correspond with the form of eqn. (48),

$$K_2=-\left(\frac{m}{n}\right)\left[(1+\lambda)\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l-1\right]$$
$$\times\sqrt{\left(\frac{\sigma_{x1}\sigma_{y1}}{\sigma_{y2}^2}\right)}\left[\frac{\cosh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad (50)$$

These results, with $\sigma_{x1}=\sigma_{y1}=\sigma_{x2}=\sigma_{y2}$, are quoted in the first row of Tables 4 and 5.

(7.3) Conducting Shell with Overhang and Zero-Resistance End-Rings

The only difference between this problem and the one discussed in Section 7.2 lies in the end conditions. The forms for J'_{x1} and J'_{y1} will be the same as in eqns. (24) and (25) respectively, but J'_{x2} and J'_{y2} will be different. The current flow at the ends is normal to the equipotential zero-resistance end-rings, and it is J'_{y2}, therefore, which is zero at $x=(1+\alpha)l$ in this case. With this modification, the same logic as previously employed gives the following results:

$$J'_{x1}=\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\cos\left(\frac{\pi}{b}py+\omega t\right)$$
$$\times\left[1-\frac{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1}{(1+\lambda')\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad (51)$$

$$J'_{y1}=\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\sin\left(\frac{\pi}{b}py+\omega t\right)$$
$$\times\left[\frac{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1}{(1+\lambda')\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad (52)$$

$$J'_{x2}=\left(\frac{h_1}{h_2}\right)\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\cos\left(\frac{\pi}{b}py+\omega t\right)$$
$$\times\left\{\frac{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2-(1+\alpha)l]}{\left(1+\frac{1}{\lambda'}\right)\cosh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}\right\} \quad (53)$$

$$J'_{y2}=(-)\left(\frac{h_1}{h_2}\right)\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}\left(\frac{\omega\sigma_{x1}bB_m}{\pi p}\right)\sin\left(\frac{\pi}{b}py+\omega t\right)$$
$$\times\left\{\frac{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2-(1+\alpha)l]}{\left(1+\frac{1}{\lambda'}\right)\cosh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}\right\} \quad (54)$$

$$\text{where}\quad \lambda'=\left(\frac{h_2}{h_1}\right)\sqrt{\left(\frac{\sigma_{x2}\sigma_{y2}}{\sigma_{x1}\sigma_{y1}}\right)}\left[\frac{\tanh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}{\tanh\frac{\pi}{b}p\alpha l\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}}\right]$$

The power is given by

$$P=P_0\left[1-\frac{\tanh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}{\frac{\pi p}{b}\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}(1+\lambda')l}\right] \quad . \quad . \quad (55)$$

The flow lines in region 1 are

$$\sin\frac{\pi}{b}py\left[(1+\lambda')\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l-\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}x_1\right]=K'_1$$
$$. \quad . \quad . \quad . \quad (56)$$

$$\text{where}\quad K'_1=\left(\frac{m}{n}\right)\left[(1+\lambda')\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l-1\right] \quad . \quad (57)$$

and in region 2 they are

$$\sin\frac{\pi}{b}py\left\{\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}[x_2-(1+\alpha)l]\right\}=K'_2 \quad . \quad (58)$$

where

$$K'_2=\left(\frac{m}{n}\right)\left[(1+\lambda')\cosh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}-1\right]$$
$$\times\sqrt{\left(\frac{\sigma_{x1}\sigma_{y1}}{\sigma_{x2}\sigma_{y2}}\right)}\left[\frac{\sinh\frac{\pi}{b}p\alpha\sqrt{\left(\frac{\sigma_{y2}}{\sigma_{x2}}\right)}l}{\sinh\frac{\pi}{b}p\sqrt{\left(\frac{\sigma_{y1}}{\sigma_{x1}}\right)}l}\right] \quad . \quad (59)$$

For comparison with formulae relating to practical tests on a uniform open-ended shell the results set out in Tables 2–5 have been derived, where appropriate, by putting $h_1 = h_2 = h$ and $\sigma_{x1}=\sigma_{y1}=\sigma_{x2}=\sigma_{y2}$ in the above expressions.

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THE MEASUREMENT OF HIGH VOLTAGES WITH INDICATING OR RECORDING INSTRUMENTS

By G. W. BOWDLER, M.Sc., Associate Member.

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SUMMARY

The paper reviews the methods by which the mean, r.m.s., or peak values of voltages ranging from 10 kV upwards may be measured by indicating or recording instruments to an accuracy within about 1%. Most of the methods use either a low-range high-impedance voltmeter or cathode-ray oscillograph in conjunction with a voltage divider or a milliammeter in series with a high impedance.

Voltage dividers suitable for use with direct, alternating and impulse voltages are considered, and, amongst the measuring instruments, the diode peak voltmeter is discussed in some detail. High-range electrostatic voltmeters are also considered.

It is concluded that there are always at least two different methods by which a particular type of voltage may be measured.

LIST OF SYMBOLS

Z_1, R_1, C_1 = Impedance, resistance, capacitance of h.v. arm of voltage divider.
Z_2, R_2, C_2 = Impedance, resistance, capacitance of l.v. arm of voltage divider.
C_e = Capacitance to earth of h.v. arm.
L = Inductance of loop between test object and voltage divider.
C_3 = Capacitance at oscillograph end of split capacitance divider.
C_K = Capacitance of delay cable connecting oscillograph to voltage divider.
Z_0 = Characteristic impedance of delay cable connecting oscillograph to voltage divider.
C' = Coupling capacitance between end of delay cable and oscillograph plate.
R' = Resistance through which bias voltage is applied to oscillograph plate.
C = Output capacitance of diode peak voltmeter.
R = Load resistance of diode peak voltmeter.
C_R = Capacitance between electrodes of diode.
R_R = Forward resistance of diode.

(1) INTRODUCTION

Up to the present, the only method of measuring peak voltages of, say, 10 kV upwards which has received official international recognition is that involving sparkover between spherical electrodes. A sphere-gap, used in accordance with B.S. 358, is a simple, inexpensive and (except for voltages having a peak duration less than about 1 microsec) reasonably accurate peak voltmeter. It is particularly useful as an independent check on the accuracy of more complicated measuring equipment and for the calibration of indicating instruments which give a continuous reading and do not involve interruption of the voltage supply.

The figures given in sphere-gap tables are derived from measurements made by more fundamental methods of measuring peak voltages. Such methods are capable of greater precision than sphere-gap methods and are often more convenient. At present, Technical Committee No. 42 of the International Electrotechnical Commission is formulating rules whereby these more fundamental methods of measuring high voltages may be approved; a general review of these methods is therefore opportune.

High voltages are used extensively to test the electric strength of insulation. Since this is very largely dependent on the peak value of the applied voltage, measurements of peak voltage are generally required in such tests. On the other hand, if the voltage is applied to a circuit in which power is dissipated, the effective or r.m.s. value of the voltage is the quantity which should be measured. In addition, particularly with impulse voltages, it is often necessary or desirable to know something about the waveshape of the voltage being measured. Measurements are not generally required to an accuracy of better than 1%, but occasionally an accuracy within 0·1% should be aimed at.

For convenience, the high voltages used in practice will be divided into the following three classes:

(*a*) Sustained unidirectional voltages, with or without an alternating component.

(*b*) Sustained alternating voltages.

Voltages of this class at a frequency of 50 or 60 c/s are employed in the great majority of h.v. tests, but there is also a limited demand for medium voltages (up to 50 kV) at audio and radio frequencies.

(*c*) Impulse voltages, i.e. transient unidirectional voltages which rise rapidly (in about 1 microsec) to a peak value and then fall to zero. Most tests are made with a wave falling to half value in about 50 microsec, but a variety of waveshapes may be used, including, as an extreme case, one which rises to and falls from a sharp peak and has a total duration of less than 1 microsec.

Although in some methods of measuring high voltages the total voltage is applied to the instrument, the great majority involve the use either of a low-range voltmeter in conjunction with a voltage divider or of a milliammeter in series with a high impedance. The ratio of the voltage divider in the one case or the magnitude of the impedance in the other should be constant at all voltages up to that which is being measured. The instrument should be connected to the earthed side of the supply; when neither side is earthed, the instrument should either be read by telescope from a safe distance or at close quarters by an observer inside a metal cage connected to the same side of the supply as the instrument. The measuring instrument should always be screened from any strong magnetic or electric fields that may exist in the neighbourhood.

(2) HIGH-VOLTAGE DIVIDERS

A voltage divider consists of two impedances (Z_1, Z_2) connected in series to which the voltage is applied. The voltage across one of the impedances Z_2 is measured by an instrument

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which should have an impedance very much greater than Z_2. The measured value, multiplied by the divider ratio $(Z_1 + Z_2)/Z_2$, gives the total voltage. The impedances of the components can be measured accurately at a low voltage; the main object in the design of a divider is to ensure that the ratio of these impedances remains as constant as possible up to the maximum working voltage. Since the h.v. component Z_1 of the divider will generally have a very high impedance it is important that stray impedances should not be inadvertently thrown in parallel with it; for this reason the l.v. component Z_2 and the lead connecting one of its terminals to Z_1 should be surrounded by a metal screen which is connected to the other (generally earthed) terminal of Z_2. The capacitance between the screen and the components which it surrounds is then effectively in parallel with Z_2.

Dividers generally incorporate either resistors or capacitors, but sometimes a combination of resistors and capacitors is used. Voltage transformers, which are used very extensively at power frequencies, may also be regarded as inductive voltage dividers with closely coupled ratio arms.

(2.1) Resistor Dividers

Resistor dividers can be used for the measurement of direct, alternating or impulse voltages, and each of these cases will, in general, require a particular type of resistor. When used on alternating or impulse voltages the response time of the divider, i.e. the difference between the time-constants of the h.v. and l.v. resistors R_1 and R_2, should be small compared with the duration of any component of the voltage wave which needs to be measured accurately. It is always better to strive for small values of time-constant in both these resistors than to try to obtain a good overall response by matching two large values of time-constant; the resistors can then be treated as good-quality components which need not always be used together (see Section 4.1). The l.v. resistor will present no difficulty; the types of h.v. resistor suitable for use on direct, alternating and impulse voltages will now be examined separately.

(2.1.1) Resistor Dividers for the Measurement of Direct Voltages

Most sources of high direct voltage have a very limited power output, so that the current available for measuring purposes rarely exceeds about 1 mA; resistances of many megohms are thus required. If wire-wound resistors are used, miles of very fine-gauge wire must be incorporated in the h.v. unit in such a way that at the working voltage it is free from corona discharge or undue temperature rise. Leakage over the insulation supporting the wire should also be negligible. From all these points of view it is an advantage to immerse the h.v. resistor in transformer oil and screen the l.v. terminal from any current that might leak over the solid insulation supporting the h.v. portion of the resistor.

A well-designed resistor of this type, due to Waterton,[1] is shown in Fig. 1. It consists of a series of disc coils wound spirally with narrow pressboard strip on which is wound, with turns slightly spaced, a still narrower strip. This narrower strip is wound with lightly oxidized bare Nichrome wire 2 mils in diameter. A stack of coils totalling about 80 MΩ and capable of withstanding 150 kV is accommodated in an oil-filled tube of resin-bonded paper $10\frac{1}{2}$ in in diameter and 18 in long with metal end fittings. Longer stacks could be used for higher voltages and there would appear to be no great difficulty in constructing a resistor of this type for operation up to 500 kV. To-day it would be preferable to use, instead of Nichrome, either of the quaternary alloys known as Evanohm and Karma, which, by suitable annealing, can be made to have an exceedingly small change of resistance (approximately 1 in 10^4) over a working

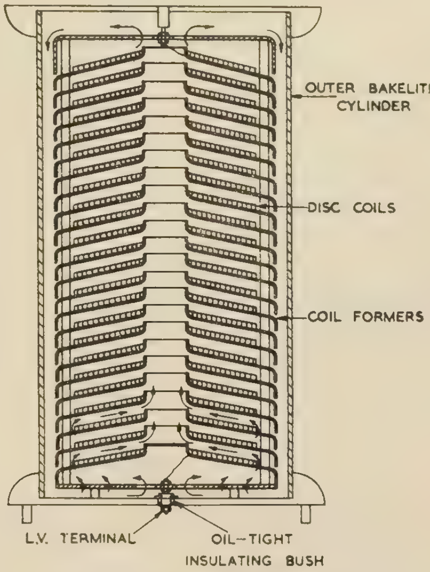

Fig. 1.—Sectional drawing of h.v. resistor, showing oil baffles.

The arrows indicate the direction of the convective oil flow.

temperature range of 100° C and whose resistivities are even greater than that of Nichrome.[2]

When the high accuracy associated with a wire-wound resistor is not required and the expense not justified, the merits of the Grade-1 thin-film type of resistor, used extensively in electronic circuits, deserve consideration. The best known of these is the 'cracked carbon' type first described by Hartmann and Dossmann[3] in which a thin adherent film of graphitic carbon is deposited at high temperature on the surface of a ceramic rod or tube which is subsequently fitted with metal end connections. The characteristics of this type and also of some others which show considerable promise (e.g. gold-platinum film and metallic-oxide film) have recently been fully described by Dummer.[4] The manufacturers of these resistors appear to cater almost entirely for the radio and electronic component trade, so that a large number of small units is generally necessary for the construction of a h.v. resistor. One-megohm resistors rated at 1 watt are convenient units to use and these should not be operated beyond their power rating; with unhindered air ventilation a rise in temperature of about 80° C and a change in resistance of approximately 2% will occur at full load. For the reasons stated in connection with wire-wound resistors, however, it is advisable to immerse the units in transformer oil. By this means the temperature rise and change of resistance on load can be reduced to about half the above-mentioned values. A resistor of this type, mounted in an oil-filled Bakelite tube $6\frac{3}{4}$ in in diameter and 7 ft in length and suitable for operation up to 500 kV, has been described by Waterton.[5]

A single large resistor unit is preferable to a chain of small ones. One manufacturer makes 90-watt units in which a helical conducting track is deposited on the outer surface of a ceramic tube 2 in in diameter and 18 in long; the resistance values range from 1 to 10 000 MΩ. One-thousand megohm units of this size have been in regular use at the National Physical Laboratory for the last decade for the measurement of direct voltages up to 100 kV. Periodical measurements of the resistance at 500 volts indicate that this falls somewhat during the first year following manufacture but settles down to a constant value which is about 3% less than the initial value. Owing to the low loading (10 watts) at 100 kV, the temperature rise is small and the change

of resistance between a low voltage and 100 kV (the maximum rated voltage) is not more than 1%. These units can be used for voltages up to 100 kV in air, but it is preferable to mount them in a 3 in diameter Perspex tube filled with oil and provided with a guard ring; they can be used in series for higher voltages.

(2.1.2) **Resistor Dividers for the Measurement of Alternating Voltages**

The time-constant of an unscreened resistor used for measuring high alternating voltages will, on account of its large size and high ohmic value, be mainly determined by the capacitances with which it is associated, and of these the capacitance to earth, C_e, generally predominates. If C_e is uniformly distributed throughout the resistor, the effective impedance (Z_1) to an applied sinusoidal voltage of frequency $\omega/2\pi$ is given by the equation

$$Z_1 = R_1\left(1 + \frac{jR_1C_e\omega}{6} - \frac{R_1^2C_e^2\omega^2}{120} - \ldots\right)$$

$$= R_1\left(1 + \frac{R_1^2C_e^2\omega^2}{180}\right)\angle \text{arc tan } R_1C_e\omega/6 \quad . \quad . \quad (1)$$

Thus the capacitance C_e causes a first-order phase error $\tan^{-1}\frac{R_1C_e\omega}{6}\left(\simeq \frac{R_1C_e\omega}{6}\text{ radian}\right)$ and a second-order error $\frac{R_1^2C_e^2\omega^2}{180}$ in the magnitude of the impedance.

Unscreened resistors consisting of wire wound on thin cards of insulating material or woven as the warp of a ribbon with a weft of silk or glass threads and designed to carry a current of 50 mA have a phase error of about 0·0003 radian at a frequency of 50 c/s when the resistance is 200 000 ohms (10 kV rating). For the same current rating and higher voltages both R_1 and C_e would increase; the phase angle would thus soon become large and, moreover, indefinite, owing to uncertainty in the value of C_e. This uncertainty can be eliminated by enclosing the resistor in an earthed case, but only at the expense of increased phase error, unless this is compensated by capacitance in parallel with the resistor.

A more general way of avoiding phase error in a resistor for use with high power-frequency alternating voltages is to divide the resistor into a number of units, each enclosed in a metal screen maintained at the mean potential of the unit so that the net capacitance current flowing out of the resistor is approximately zero. The screen potentials are generally derived from an auxiliary resistor connected in parallel with the main one. In this way resistors about 1 MΩ in value have been constructed for use at a frequency of 50 c/s and voltages up to 100 kV having phase errors not greater than 0·0002 radian and resistances which are effectively the same as the d.c. values; they are very bulky and power-consuming pieces of equipment, however.[6] In a method of avoiding phase errors which the author considers promising and worthy of investigation, the resistor element is wound uniformly on a cylindrical support (an Ayrton double-layer winding may be necessary to reduce the inductance) which is then mounted between large parallel plate electrodes, the lower one of which serves as a guard-ring for the l.v. terminal of the resistor.

In cases where only the magnitude of the impedance is significant (as in the peak or r.m.s. voltage measurements considered here) a phase error of about 0·1 radian can be tolerated; in these circumstances thin-film resistors of the order of 100 megohms in value can be used at power frequencies. For example, the calculated capacitance to earth of a 90-watt unit of the size quoted in the last paragraph of Section 2.1.1 when standing on an earthed plane is about 10 pF. If the resistance is 200 MΩ and the frequency of the applied voltage 50 c/s, the calculated phase error is 0·105 radian. The measured phase error of such a unit was found to be 0·07 radian; the difference between this and the calculated value could be ascribed to a capacitance of 0·56 pF between the end fittings of the resistor. It is not practicable, as in the case of direct voltage measurements, to use several of these units in series for voltages much higher than 100 kV, since the errors will be approximately proportional to the square of the number of units and a condition is soon reached in which these errors are excessive and critically dependent on the disposition of each resistor with respect to neighbouring objects. Once again, the practical voltage limit for resistors used at 50 c/s appears to be about 100 kV.

(2.1.3) **Resistor Dividers for the Measurement of Impulse Voltages.**

When resistors for use with alternating voltages tend to be limited, by reason of the errors associated with their stray capacitances, to a voltage of about 100 kV at 50 c/s and correspondingly lower voltages at higher frequencies, it may seem somewhat paradoxical to state that resistor dividers are suitable for the measurement of impulse voltages up to 1 or 2 MV. The reason for this is that dividers of low resistance can be used with impulses without the dissipation of large amounts of energy. Whereas the current in a d.c. divider may be 1 mA and in a power-frequency a.c. divider 10 mA, that in a divider for impulse voltages may be anything up to 100 amp.

As in the case of a.c. dividers, the chief source of error is the earth capacitance C_e of the h.v. resistor. If a constant voltage V is suddenly applied at time $t = 0$ to the resistor, the current i at the earthed end, on the assumption that the capacitance is uniformly distributed, is given by the equation

$$i = \frac{V}{R_1}\left[1 + 2\sum_{m=1}^{m=\infty}(-1)^m \exp\left(-m^2\pi^2 t/C_eR_1\right)\right] \quad . \quad (2)$$

A graph showing the relation between i and t is shown in Fig. 2. Thus a voltage wave with a vertical front produces a current wave

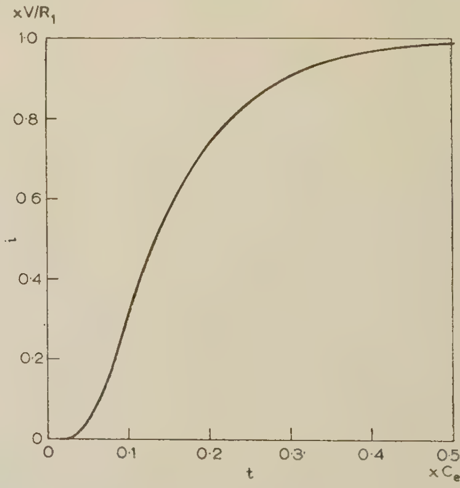

Fig. 2.—Graph of current at earthed end of a resistance R_1 having uniformly distributed earth capacitance C_e, in response to a constant voltage suddenly applied at time $t = 0$.

with a front of finite duration. The current is within 1% of its final value in a time equal to $0{\cdot}53C_eR_1$, and in general a divider incorporating the resistor should not be relied upon for the measurement of voltages having a duration less than this.

A resistor for 1 MV must be about 200 cm in length to avoid surface flashover. If it is in the form of a cylinder standing vertically on an earthed plane its capacitance to earth will be about 30 pF, which, in conjunction with a resistance of

33 000 ohms, gives a time-constant of 1 microsec. This will permit the measurement to an accuracy within 1% of the peak value of a 1/50 or 1/5 impulse wave[7]. When it is necessary for the front of such waves to be recorded with reasonable accuracy or for the peak value of a wave chopped on the front by breakdown of a test sample to be measured, then the product C_eR_1 should be reduced to about 0·1 microsec by reduction of the value of R_1 or C_e or both. The effective capacitance to earth can be reduced considerably by placing the resistor in a uniform or nearly uniform field. By fitting a large conical electrode to the upper end of a 30 000-ohm resistor, Howard[8] has reduced the error in recording the peak value of a wave chopped in a few tenths of a microsecond from approximately 20% to 1%.

All the resistors in a divider for impulse voltage measurements should be designed to have very small residual inductances. Ribbon, 8 cm in width, woven with a warp of constantan wire has been used at the N.P.L. for both the h.v. and l.v. resistor units. In the h.v. units the ribbon is mounted longitudinally on a resin-bonded paper tube having a circumference slightly greater than the width of the ribbon. This is then immersed in transformer oil in a Perspex tube of 3·8 cm bore fitted with metal ends, and degassed by subjection to a vacuum. Units 48 in in length can be used to measure voltages up to 500 kV and can be assembled in series for higher voltages.

The resistance material should have sufficient thermal capacity to absorb the energy dissipated by the surge without undue temperature rise. Units of the above-mentioned size, for instance, when subjected to a 500 kV impulse having a 1/50 microsec waveshape will rise in temperature by 55° C when made from ribbon woven with wire of diameter 0·1 mm giving a resistance of 22 000 ohms, and by 130° C when wire of diameter 0·2 mm and resistance 3 600 ohms is used. In the interval between successive impulses the resistor should be able to cool down substantially to room temperature.

It is generally necessary, when recording impulse voltages, to delay for about 0·5 microsec the arrival at the oscillograph of the voltage obtained from the divider by connecting these two components together via a length of low-loss coaxial cable, which, when a resistor divider is used, can be terminated by a resistance equal to its characteristic impedance [Z_0 in Fig. 3(*a*)]. If the d.c. resistance of the cable conductor is less than about 1% of the characteristic impedance, the attenuation of a 1/50 microsec wave due to the cable can be neglected. When recording waves chopped within a microsecond, however, it is necessary to use a delay cable having a conductor resistance less than 0·1% of the characteristic impedance, if serious errors due to attenuation are to be avoided (see Reference 8).

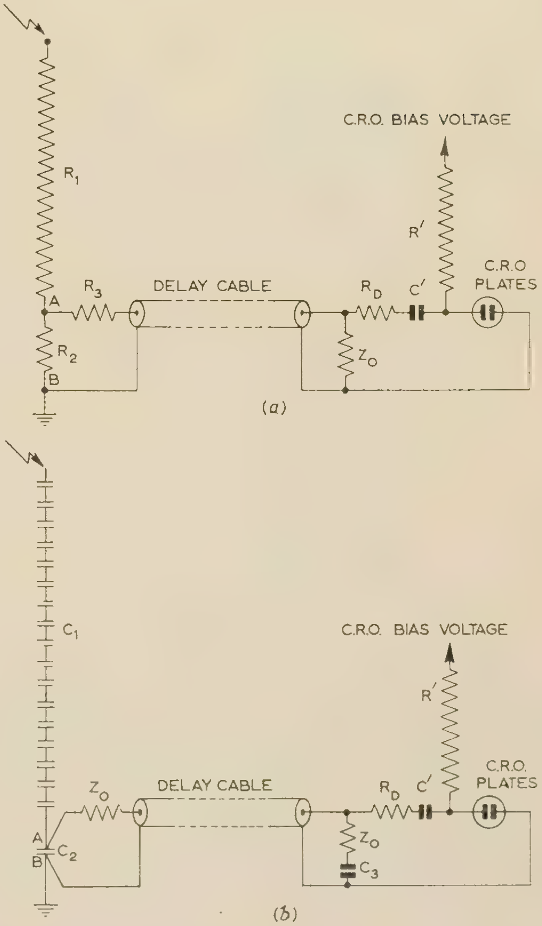

Fig. 3.—Circuit diagrams of voltage dividers for the recording of impulse voltages using low-loss delay cable of characteristic impedance Z_0 and capacitance C_K.

(*a*) *Resistor Divider.* Ratio $= \dfrac{R_1 + R_2'}{R_2'} \dfrac{R_3 + Z_0}{Z_0}$

where $R_2' = \dfrac{R_2(R_3 + Z_0)}{R_2 + R_3 + Z_0}$

and R_3 includes d.c. resistance of delay cable.

(*b*) *Capacitor Divider.* Ratio $= \dfrac{C_1 + C_2 + C_3 + C_K}{C_1}$

where $C_1 + C_2 = C_3 + C_K$

(2.2) Capacitor Dividers

Capacitor dividers are not satisfactory for the measurement of direct voltages, but for alternating voltages they have the advantage that they consume no power and can be used at higher voltages or frequencies (or both) than any other form of divider; they can also be used for the measurement of impulse voltages.

To prevent the accumulation of stray d.c. charge on a capacitor divider it is generally necessary to shunt the l.v. arm by a high resistance.

(2.2.1) Capacitor Dividers for the Measurement of Alternating Voltages.

The h.v. arm generally consists of a capacitor with a gaseous dielectric and concentric cylindrical electrodes designed to be free from corona discharge. The l.v. electrode is screened from the effects of stray fields due to neighbouring conductors by a third (guard) electrode. With smooth electrode surfaces and dry air at normal density as dielectric, voltage gradients up to about 10 kV r.m.s./cm can be reached between the electrodes before flashover occurs; capacitors of this type having calculable capacitances and rated for use at voltages up to 300 kV r.m.s. have been described by Churcher and Dannatt.[9]

Since the electric strength of a gas increases with its density, the size of a capacitor for a given voltage rating can be reduced by enclosing the electrodes in a pressure vessel; this also protects the electrodes from atmospheric pollution. Standard capacitors, using nitrogen or carbon dioxide contained at a pressure of 14 atm in a resin-bonded paper tube which serves as a pressure vessel and as an insulator for the h.v. electrode, have been made for use at voltages up to 900 kV r.m.s.[10] (Fig. 4).

The l.v. arm may well consist of a good-quality mica capacitor.

(2.2.2) Capacitor Dividers for the Measurement of Impulse Voltages.

Dividers for use with impulse voltages are somewhat complicated by the need for a delay cable between the divider and the oscillograph; only with resistor or parallel resistor-capacitor dividers can the ratio theoretically be constant. Burch[11] has

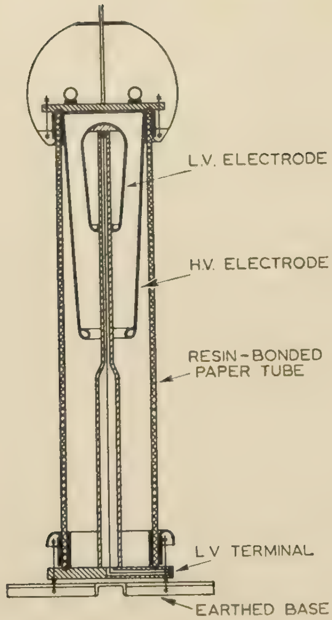

Fig. 4.—Sectional drawing of 900 kV capacitor.

shown, however, that with a capacitor divider arranged as in Fig. 3(*b*) the voltage initially appearing at the oscillograph at time $t = \tau$, in response to a constant voltage suddenly applied to the divider at time $t = 0$, is the same as the final value. In the interim, the voltage at the oscillograph rises to a maximum at time $t \simeq 3\tau$. The amount of this rise, expressed as a percentage of the initial (or final) value, at $t = 3\tau$, has been calculated by Howard[8] for various values of $\eta = C_K/(C_1 + C_2 + C_3)$ and found to be less than 1% for values of η below 0·08.

For a delay of 0·5 microsec the value of C_K will be about 0·005 μF; hence the minimum total capacitance $(C_2 + C_3 + C_K)$ of the l.v. arm which is necessary to avoid errors greater than 1% due to reflections in the delay cable is approximately 0·06 μF. At 500 volts, which is generally required for the oscillograph, the charge on the l.v. arm will therefore be at least 30 microcoulombs and the h.v. capacitor should also be capable of storing a charge of this magnitude.

It has been assumed so far that C_1, C_2 and C_3 [Fig. 3(*b*)] are pure capacitances. Imperfections of the dielectric and series resistance or inductance will invalidate this assumption, and of these the last will in practice be the most important, especially when measurements within a microsecond are required. Capacitors having a resonance period short compared with the duration of the wavefront of the impulse are necessary; this condition is more difficult to fulfil in the low-voltage than in the high-voltage arm, but bushing-type paper-dielectric capacitors designed for suppression of mains-borne interference in radio equipment have proved satisfactory in this respect as l.v. units of the divider.

In contrast to the a.c. case, an unscreened 2-terminal capacitor is used in the h.v. arm. This generally consists of a number of paper-dielectric units assembled in series and immersed in oil in a cylindrical container with metal end fittings. Such an assembly 1 m in length can be used up to 400 kV and may have a capacitance of about 1 000 pF; similar assemblies can be stacked in series for higher voltages.

When the voltage to be measured is high it is not possible to locate the divider very close to the test object; the voltages across these two components may therefore differ appreciably. In Fig. 5 the test object, which is assumed to have a low impedance,

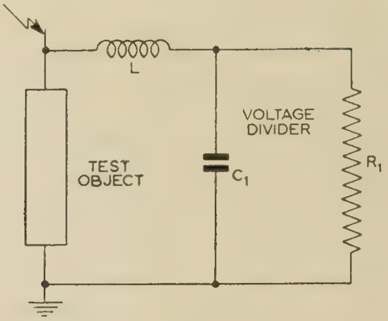

Fig. 5.—Diagram of connections between test object and voltage divider to illustrate the possibility of overvoltage on the divider during impulse tests.

is connected to the divider, consisting of a resistance R_1 in parallel with a capacitance C_1, via a loop of inductance L. If R_1 is greater than $\frac{1}{2}\sqrt{(L/C_1)}$ this circuit is oscillatory and a unit-function voltage applied to the test object will result in a voltage v on the divider given approximately by the equation $v = 1 - \varepsilon^{-t/2C_1R_1} \sin [t/\sqrt{(LC_1)} + \phi]$.

A typical value for L would be 10 μH and, with a capacitance divider, C_1 would be several hundred picofarads and R_1 very large. Hence, a lightly damped oscillation decaying with a long time-constant $(2C_1R_1)$ would be superimposed on the applied wave. It is advisable in this case to insert sufficient series resistance in the h.v. connection between the test object and the divider to cause critical damping. The divider voltage would then rise to within 1% of the applied voltage in a time equal to about $4\sqrt{(LC_1)}$.

Even with a resistor divider there may be sufficient stray capacitance in parallel with the resistor to cause oscillations, but these would be quickly damped without the aid of series resistance which, in this case, would be undesirable.

(2.3) Mixed (Resistor-Capacitor) Dividers

For the recording of impulse voltages, dividers incorporating series or parallel arrangements of resistors and capacitors are sometimes used. The series arrangement is necessary when the impulses are superimposed on an alternating voltage and a divider having a finite impedance at infinite frequency is required; the parallel arrangement can be used to improve the response of a high-resistance divider. Further details of these dividers can be found in References 8 and 11.

(2.4) Voltage Transformers

Voltage transformers are used extensively at power frequencies, where they permit the use of relatively low-impedance measuring instruments such as dynamometer voltmeters and wattmeters. They are made to operate at all standard line voltages, and their ratio errors at voltages ranging from 20 to 120% of the rated value are generally well within 1%.[12] They should be used with caution when the voltage is known to possess a badly distorted waveshape.

(3) MEASURING INSTRUMENTS USED IN CONJUNCTION WITH VOLTAGE DIVIDERS

A high-impedance voltmeter which has a negligible shunting effect on the l.v. arm is the ideal instrument to use in conjunction with a voltage divider. In this respect the cathode-ray oscillograph and the electrostatic voltmeter are pre-eminent. Another instrument that is often used and the shunting effect of which can generally be reduced to negligible proportions is the diode peak voltmeter. All these instruments are capable of an accuracy of 1% or better and cover a very wide range of frequency.

(3.1) Cathode-Ray Oscillograph

The cathode-ray oscillograph is generally associated with the measurement of impulse voltages, but its value as a measuring or monitoring instrument for direct and alternating voltages should not be overlooked. The voltage required on the deflecting plates is generally within the range 50–500 volts and the capacitance between these plates is about 10 pF. The cathode beam should be well screened from influence by stray electric or magnetic fields and accelerated by a stable, constant voltage. When used with a recurrent time-sweep, the waveshapes of alternating voltages can be readily observed or recorded, and any abnormalities (e.g. very sharp peaks, multiple peaks, or amplitude modulation) which might vitiate other methods of measuring the peak voltage can thus be revealed.

The peak value of alternating or rippled direct voltage can readily be measured by opposing it with a direct voltage and applying the resultant to the oscillograph plates, one of which is earthed. The direct voltage is adjusted until the extremity of the oscillation due to the alternating component is brought to the position on the screen occupied by the beam when both plates are earthed; a measurement of this voltage then gives the peak value.[13]

When used with impulse or very-high-frequency alternating voltages, the inductance of the connections between the oscillograph plates and the divider should be reduced to a minimum and a resistance R_D of about 300 ohms introduced into the lead to the non-earthed plate (Fig. 3). For this reason the end of a delay cable used in conjunction with the oscillograph should be plugged into a terminating socket mounted on the oscillograph case near to the deflecting plates. The peak value of an impulse is derived from measurements on an oscillogram on which are recorded

(a) The impulse wave.
(b) A zero line.
(c) A voltage calibrating line.

To utilize the full width of the oscillograph screen the zero line should be biased to one side so that the peak of the wave carries the beam to the other side of the screen. The calibrating voltage should cause a deflection of the beam roughly equal to that of the impulse, and both the zero and calibrating lines should be recorded at about the same time as the impulse, so that errors due to any slow drift in the sensitivity of the oscillograph may be eliminated. The necessary bias and calibrating voltages should be applied, through a high resistance R', to the deflecting plate which is coupled through a capacitance C' and the damping resistance R_D (Fig. 3) to the non-earthed side of the impulse. The time-constant $C'R'$ should be large compared with the duration of the impulse, and the insulation resistance of C' should also be very large compared with R'.

Sometimes, in tests involving breakdown at or near the peak of the wave, spurious deflections due to incomplete screening of the oscillograph or to large transient currents in the outer conductor of the delay cable may occur and give incorrect records of the peak voltage. Such deflections can be detected by disconnecting the inner conductor of the delay cable from the tapping point A (Fig. 3) on the voltage divider, connecting it to the earth point B and operating the impulse generator. If in these conditions an undisturbed zero line is not recorded, the shielding or earthing, or both, should be improved until the disturbance is eliminated.

(3.2) Electrostatic Voltmeter

Portable electrostatic voltmeters giving full-scale deflection with about 100 volts, having a capacitance of about 30 pF and an accuracy within 0·5% over the upper part of their scale at frequencies up to 5 Mc/s are available. They are ideally suited, in conjunction with voltage dividers, for the measurement of the r.m.s. values of a very wide range of direct or alternating voltages. As with the cathode-ray oscillograph, the inductance of the connections between the divider and the instrument should be reduced as much as possible when measuring very-high-frequency voltages. For instance, in the case of the voltmeter quoted above, the inductance should not exceed 0·1 μH when measurements are made at a frequency of 5 Mc/s.

(3.3) Diode Peak Voltmeter

The diode peak voltmeter (Fig. 6) can be used to measure the peak value of direct, alternating or impulse voltages. The

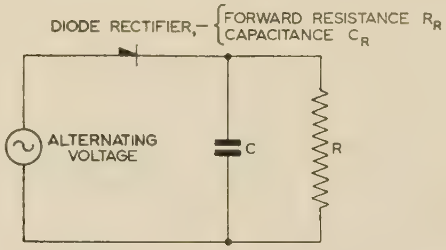

Fig. 6.—Circuit diagram of diode peak voltmeter.

capacitor C is charged to the peak value of the applied voltage through the rectifier, which, in the case of alternating voltages, must be able to withstand twice the peak voltage in the reverse direction. If the diode be regarded as a capacitance C_R in parallel with a resistance R_R in the conducting direction and infinite resistance in the reverse direction, and if a capacitance C in parallel with a resistance R* be connected to the d.c. output of the diode, with a sinusoidal input of frequency $\omega/2\pi$, the output voltage falls short of the true peak by the following fractional amounts:

(a) C_R/C due to the a.c. component of voltage across C.
(b) $\pi/RC\omega$ due to the voltage ripple on C caused by leakage through R.
(c) $1{\cdot}7(R_R/R)^{2/3}$ due to the resistance of the rectifier.

The proof is given in Section 9.

It is not difficult, by making C large, for items (a) and (b) to be rendered negligible. On the other hand, C should not be so large that the instrument is sluggish in response to a fall in voltage. For the error under item (c) to be 1 or 0·1%, the ratio R/R_R must be 2200 or 70000, respectively.

The shunting effect of the diode on the divider has so far been ignored, but if this is taken into account the following alternative or additional fractional error (see Section 9) occurs in the peak voltmeter reading owing to the flattening of the peaks of the voltage wave on the l.v. arm of the divider by the pulses of current passed by the diode:

(d) With a resistor divider having a l.v. arm of resistance R_2, the error under item (c) is increased to $1{\cdot}7[(R_R + R_2)/R]^{2/3}$.

(e) With a capacitor divider having a l.v. arm of capacitance C_2, the additional error is $\pi/RC_2\omega$.

Hence for high accuracy the resistance of the d.c. voltmeter and the back resistance of the rectifier should both be very large compared with the forward resistance of the rectifier and the impedance of the l.v. arm of the divider. With typical values of divider current at a frequency of 50 c/s the current through R should not exceed about 1 μA if an accuracy within 0·1% is desired.

* Any back leakage through the rectifier is taken into account in the value of R.

The characteristics of practical rectifiers conform only approximately to the conditions which have been assumed above; the transition from a low to a high resistance in the region of zero applied voltage is gradual instead of abrupt. Thermionic diodes are preferred and the Service type CV140 is recommended; owing to the small current which flows with zero applied voltage the peak voltmeter reading may be 0·1 or 0·2 volt greater than that predicted by the simple theory given above (see Reference 19), but this error can be made negligible by operating the rectifier at its maximum rated voltage. In cases where it is inconvenient to use a thermionic rectifier the recently developed silicon junction diodes, having a forward resistance of about 3 ohms and capable of withstanding 120 volts in the reverse direction, provide a suitable alternative. These rectifiers become appreciably conductive only when the applied voltage is about 0·6 volt, so that a correction of this amount should be added to the peak voltmeter reading when they are used.

When the diode peak voltmeter is used with voltages of other than sine-wave form, the errors due to the forward resistance of the rectifier will depend on the shape of the voltage wave in the vicinity of the peak. Generally this will approximate to that of the peak of a sine wave having the same amplitude as, but a frequency n times that of, the wave under investigation; the errors will then be as given under items (*c*) and (*d*) above, except that R is replaced by R/n. Thus for waves with sharp peaks, corresponding to $n > 1$, values of R greater than those required with a sine wave are necessary.

An ingenious circuit, which is essentially a diode peak voltmeter draining negligible power from the circuit to which it is connected, has recently been described by Baker.[14] This circuit would be useful in cases where an electrostatic voltmeter or galvanometer was not available for use in conjunction with a diode peak voltmeter and where measurements were required at only one frequency.

When using a diode peak voltmeter in conjunction with a capacitor divider, d.c. bias on the l.v. capacitor should be eliminated. Rabus[15] has shown that this can best be effected by connecting a second diode peak voltmeter circuit, identical with the first except that it should be arranged to measure the peak of opposite polarity, across the l.v. capacitor.

The diode peak voltmeter has been used to obtain a rapid and accurate measurement of the peak values of impulse voltages. A capacitance of the order of 100 pF can be charged within a microsecond by a thermionic rectifier having a high emission to the true peak value of an applied impulse, but in general the charge leaks back appreciably through the rectifier before the voltage on the capacitor can be measured. This difficulty can be overcome by allowing the capacitor to discharge through a high resistance into either a ballistic galvanometer[16] or a much larger capacitance connected to a low-range electrostatic voltmeter.[17]

(4) MEASURING INSTRUMENTS USED IN SERIES WITH A HIGH IMPEDANCE

The impedances required for the h.v. arm of a divider can often more conveniently be used in series with a low-impedance current-measuring instrument than as part of a divider to measure high voltages.

(4.1) Milliammeter in Series with a Resistor

A moving-coil milliammeter in series with a high resistance is the obvious way of measuring the mean value of a voltage, and is that used most frequently for direct voltages. If the amplitude of any superimposed alternating component does not exceed about 10% of the mean value of the voltage, the difference between the mean and r.m.s. values is negligible. The amplitude of the alternating component can be measured by the method described in Section 4.2, and this, added to the mean, will generally give the peak value of a rippled direct voltage.

If the moving-coil instrument is replaced by a moving-iron dynamometer or thermal milliammeter, the r.m.s. value of the voltage is obtained, and measurements of alternating voltages can be made up to a frequency which, in general, will be limited by the errors associated with the stray capacitances of the series resistor.

(4.2) Rectifier Milliammeter in Series with a Capacitor

If the charging current of a h.v. capacitor to which an alternating voltage is applied is passed through a moving-coil milliammeter via a commutator arranged so as to reverse the connections to the instrument every half-cycle, the mean current is equal to $2fC_1(V_1 - V_2)$, where f is the frequency of the applied voltage, C_1 the capacitance, and V_1 and V_2 are the voltages on the capacitor at successive instants of commutation. A maximum current can be obtained by adjustment of the commutator and this will be equal to $4fC_1V$*, assuming that the positive and negative peaks of amplitude V are equal and separated by half a period. This method of measuring peak voltages, often associated with the names of its authors,[18] is used extensively at power frequencies. It is possible to use rectifiers instead of a mechanical commutator, and the restriction on the positive and negative peaks being separated by half a period is then removed, but errors are incurred if the voltage wave contains subsidiary peaks or if the rectifiers are operating under adverse conditions; both these conditions can generally be avoided and measurements obtained accurate to better than 1%.[19] The elimination of a mechanical rectifier also enables peak voltages to be measured by this method over a very wide range of frequencies.[20]

When using this peak voltmeter in breakdown tests, a large transient current occurs at the instant of breakdown and steps should be taken to divert this current from the rectifiers and measuring instrument.

The generating voltmeter, devised by Kirkpatrick[21] for the measurement of high direct voltages, is closely allied to the Chubb–Fortescue peak voltmeter just described, the only difference being that in the former instrument the capacitance is made to vary cyclically f times a second between the values C_{max} and C_{min}. Thus, with a constant voltage V, the mean rectified charging current is equal to $2fV(C_{max} - C_{min})$. The Kirkpatrick voltmeter is generally used in conjunction with totally enclosed Van de Graaff generators and has proved to be an accurate and reliable instrument. It is generally calibrated at one or more fixed points which are determined by nuclear reactions brought about by bombardment of suitable targets with particles which have been accelerated by the voltage in question, in which case it is not necessary to measure the values of C_{max} or C_{min}.

(5) HIGH-VOLTAGE MEASURING INSTRUMENTS

Electrostatic voltmeters are made for the direct measurement of the r.m.s. values of voltages ranging up to several hundred kilovolts. These instruments are generally based on the Kelvin attracted-disc electrometer, in that the voltage to be measured is applied to a pair of parallel plate electrodes and the force acting on a disc which occupies the centre portion of one of these electrodes is used to measure the voltage. Generally the disc is displaced slightly by the attractive force, and this causes a pointer or light-beam to move over a scale, the deflection being

* In many cases only one half-cycle of the capacitor current is passed through the measuring instrument; the mean current is then $2fC_1V$.

Table 1

APPLICABILITY OF METHODS OF MEASUREMENT OF HIGH VOLTAGES

Method of measurement	Direct voltage		Alternating voltage				Peak impulse voltage
			Power frequency		High frequency		
	Mean or r.m.s.	Peak	r.m.s.	Peak	r.m.s.	Peak	
L.V.E.S. voltmeter with resistor divider	*		*				
Diode peak voltmeter with resistor divider		*		*			*
C.R.O. with resistor divider		*		*			*
L.V.E.S. voltmeter with capacitor divider			*		*		
Diode peak voltmeter with capacitor divider				*		*	*
C.R.O. with capacitor divider				*		*	*
R.M.S. voltmeter with voltage transformer			*				
Diode peak voltmeter with voltage transformer ..				*			
C.R.O. with voltage transformer				*			
Moving-coil milliammeter in series with resistor ..	*						
R.M.S. milliammeter in series with resistor	*		*				
Rectifier milliammeter in series with capacitor .. .. (Chubb–Fortescue peak voltmeter)				*		*	
Rectifier milliammeter in series with capacitance which varies cyclically with time in synchronism with any a.c. component of the voltage (generating voltmeter)		*		*			
H.V.E.S. voltmeter	*		*		*		

L.V.E.S. denotes low-voltage electrostatic.
H.V.E.S. denotes high-voltage electrostatic.
C.R.O. denotes cathode-ray oscillograph.

roughly proportional to the square of the voltage gradient between the main electrodes.[22] For a given separation between these electrodes a 2 : 1 range of voltages can be measured to an accuracy within 1%, but, as the separation can also be varied, a much wider range of voltages than this can be covered by a single instrument. Such instruments need to be calibrated.

If the force is measured whilst the disc is accurately coplanar with the surrounding guard plate, the voltage can be calculated from a knowledge of this force and of the electrode dimensions and spacing, and no other calibration is needed. An absolute instrument of this type can be made into a direct-reading instrument by operating it so that the electrostatic force on the disc is constant. The electrode spacing necessary to bring the disc into the complanar position is then proportional to the voltage being measured and, by suitable design, a direct reading of voltage can be obtained on a linear scale.[23]

(6) CONCLUSION

In the review of the methods of measuring high voltages given above it has not been possible to deal more than superficially with any particular one. It is evident, however, that numerous well-tried methods exist whereby the peak or r.m.s. values of high direct, alternating or impulse voltages may be measured to an accuracy within about 1%. The different methods are largely summarized in the first column of Table 1 and their applicability is indicated by asterisks in the succeeding columns. In the case of alternating voltages the Table makes additional provision for those methods which are applicable to frequencies ranging up to several megacycles per second. The number of asterisks in each column indicates the number of different methods by which the parameter indicated at the head of the column may be measured; in no case is this less than two.

(7) ACKNOWLEDGMENTS

The work described above has been carried out as part of the research programme of the National Physical Laboratory, and the paper is published by permission of the Director of the Laboratory. Permission for the reproduction of Fig. 1 has been given by the Editor of the *Journal of Scientific Instruments* and for that of Fig. 2 by the firm of Hartmann and Braun.

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(9) APPENDIX

Errors of Diode Peak Voltmeter

The errors of the diode peak voltmeter are each calculated separately on the assumption that they are small and that the other errors are negligible. The total error is in general somewhat less than the sum of the errors thus calculated.

(*a*) If R is infinite, the direct voltage on C will build up until the rectifier just ceases to pass current. This condition is reached when the voltage across the rectifier is zero at the instant when the alternating voltage reaches its peak value. Since a fraction $C_R/(C_R + C)$, approximately equal to C_R/C, of the alternating-voltage appears across C, the direct voltage and hence the mean voltage on C will fall short of the true peak value by this amount.

(*b*) If R is finite, the voltage on C will fall exponentially with a time-constant RC during the period (approximately $2\pi/\omega$) between successive recharging cycles. The amplitude of the voltage ripple on C is therefore approximately $2\pi/RC\omega$ of the total voltage and the mean voltage on C falls short of the peak value by half this amount.

(*c*) Suppose that the time-constant RC is so large that the voltage ripple on C is negligible, and let the voltage on C due to an applied alternating voltage of amplitude V be V'. The charge Q passed by the rectifier for the brief period near the peak of the wave when the applied voltage exceeds V' must equal the total charge lost by leakage through R per cycle. Thus

$$Q = \frac{2}{R_R}\int_0^{\alpha/\omega} V\cos\omega t - V'dt \quad \text{where } V'/V = \cos\alpha$$

$$= \frac{2}{R_R}\left[\frac{V}{\omega}\sin\omega t - V't\right]_0^{\alpha/\omega}$$

$$\simeq \frac{2\alpha(V - V')}{\omega R_R}$$

Also
$$Q = \frac{2\pi V'}{\omega R}$$

from which
$$\frac{V - V'}{V'} = \frac{\pi}{\alpha}\frac{R_R}{R}$$

or
$$1 - \cos\alpha = \frac{\pi R_R}{R}\frac{\cos\alpha}{\alpha}$$

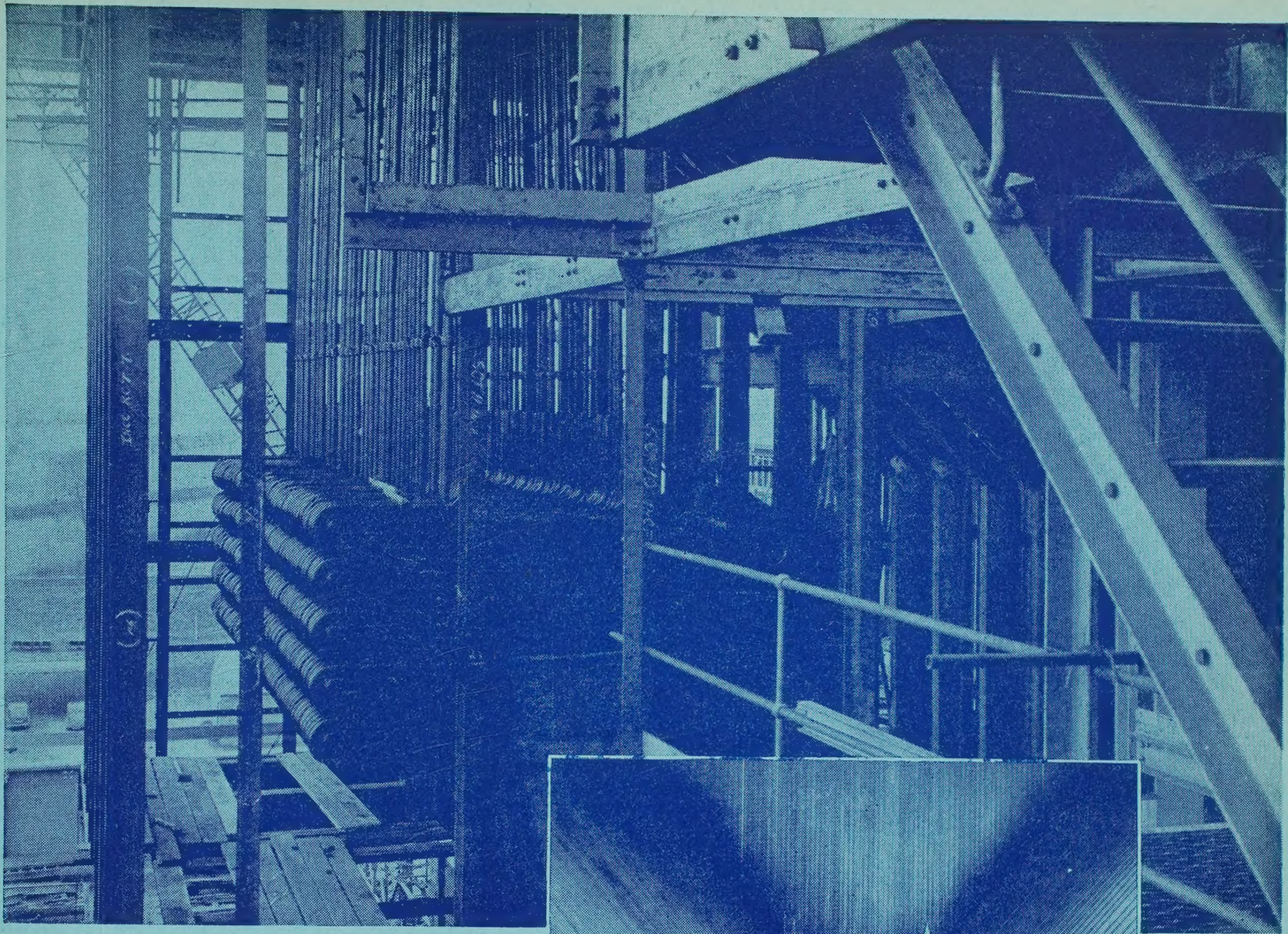
But
$$\alpha \simeq \sqrt{[2(1 - \cos\alpha)]} \text{ when small}$$

So that
$$(1 - \cos\alpha)^{3/2} \simeq \frac{\pi}{\sqrt{2}}\frac{R_R}{R}$$

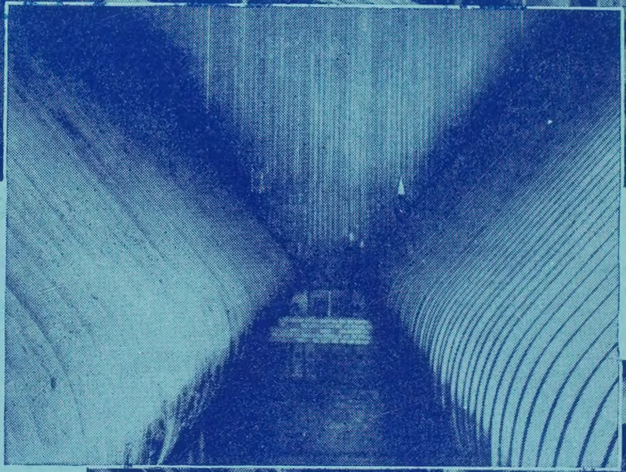
Hence
$$1 - \cos\alpha \simeq 1{\cdot}7(R_R/R)^{2/3}$$

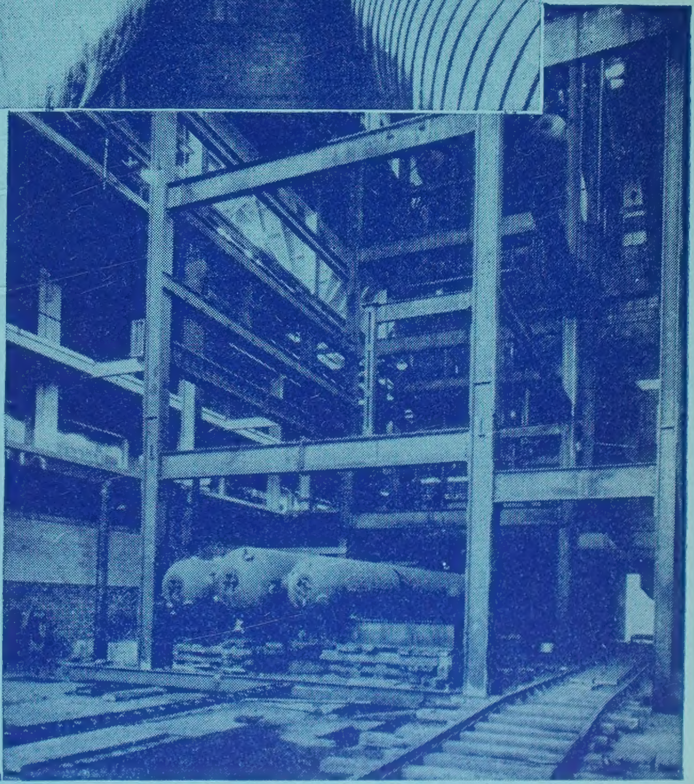
(*d*) When the diode peak voltmeter is used in conjunction with a resistor divider having a l.v. arm of resistance R_2, a simple application of Thévenin's theorem shows that the error under item (*c*) above is increased to the value corresponding to the rectifier having a resistance of $R_R + R_2$.

(*e*) When used with a capacitor divider having a l.v. arm of capacitance C_2, the charge $2\pi V/\omega R$ passed by the rectifier when the voltage is near its peak will cause the voltage on C_2 to fall by $2\pi V/\omega RC_2$. Half this charge will flow before and half after the peak voltage occurs on C_2. Therefore the fractional drop in the peak voltage on C_2 is equal to $\pi/RC_2\omega$.



Views of typical boiler installations.





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